LENA
with a focus on photosensor R&D

Marc Tippmann
for the LENA working group

Project X Physics Study 2012, Fermilab
2012/06/20

Overview

Low Energy Neutrino Astronomy

- Physics potential
- Detector layout
- Demands on the detector
- Photosensors
  - Requirements
  - Candidate photosensors
  - Measurement of sensor properties
  - Optical module for PMTs

Neutrino physics: Status

Particle physics

Neutrino properties

m_1
✓ Δm_{12}^2
✓ Δm_{23}^2
Mass hierarchy
Majorana / Dirac
✓ ϑ_{12}
✓ ϑ_{23}
✓ ϑ_{13}
Sterile neutrinos
δ_{CP}

Astroparticle physics

Galactic supernova neutrinos
Diffuse supernova neutrinos
Solar neutrinos
High-energy neutrinos
Cosmological neutrinos
Atmospheric neutrinos
Dark Matter annihilation/decay

Geophysics

Geoneutrinos

Neutrino physics: Status

Particle physics

Neutrino properties

- m_1 — *SNO+*
- ✓ Δm_{12}^2 — **KamLAND**
- ✓ Δm_{23}^2
- Mass hierarchy
- Majorana / Dirac — *SNO+*
- ✓ ϑ_{12}
- ✓ ϑ_{23}
- ✓ ϑ_{13} — **Double Chooz, Daya Bay, RENO**
- Sterile neutrinos
- δ_{CP}

Astroparticle physics

- Galactic supernova neutrinos — **Baksan**
- Diffuse supernova neutrinos
- Solar neutrinos — **Borexino,** *SNO+*
- High-energy neutrinos
- Cosmological neutrinos
- Atmospheric neutrinos
- Dark Matter annihilation/decay

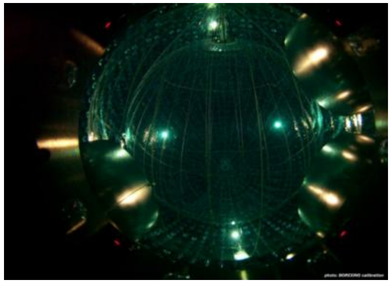
Geophysics

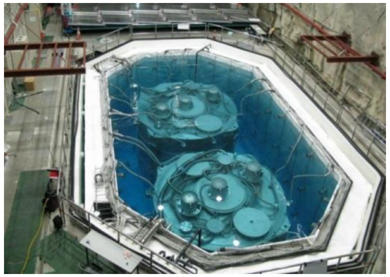
Geoneutrinos — **Borexino, KamLAND,** *SNO+*

Liquid scintillator detectors so far have made great contributions already with relatively small target masses:

Baksan (330t), KamLAND (1kt),
Borexino (280t), Double Chooz (8.3t), Daya Bay (20t), RENO (16t)
near future: SNO+ (780t)

What could we achieve with a 50kt detector?





Neutrino physics: Possible contributions from LENA

Particle physics

Neutrino properties

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Nucleon decay

Astroparticle physics

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Geophysics

Geoneutrinos

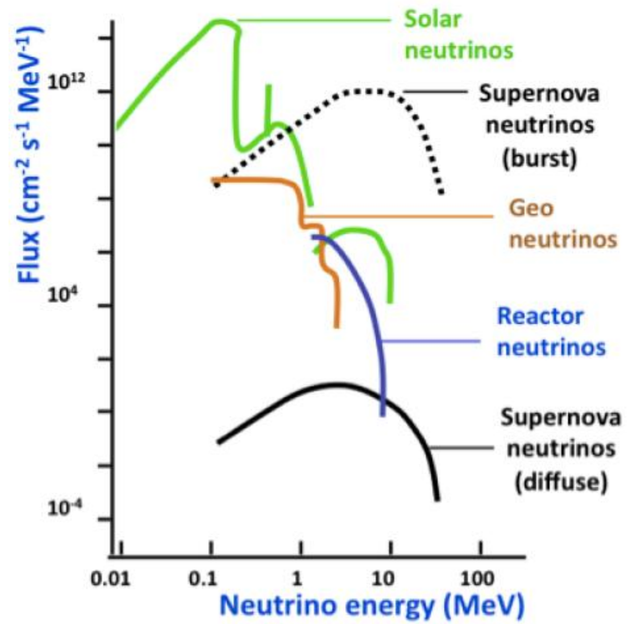
Artificial sources

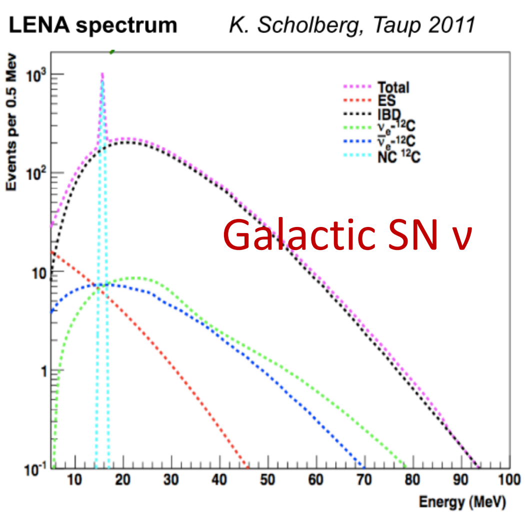
Neutrino beam
Radioactive neutrino source
Pion decay-at-rest beam
Reactor neutrinos

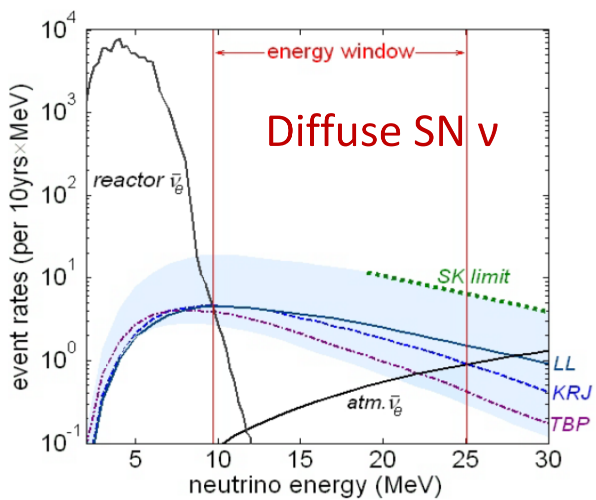
LENA
Low
Energy
Neutrino
Astronomy

Physical goals: Natural sources

- **Galactic supernova neutrinos:** Observe neutronisation burst, time-resolved cooling phase, separation of core collapse supernova models, trigger for gravitational wave detectors, possibly mass hierarchy, θ_{13}
- **Diffuse supernova neutrinos:** First detection, average SN neutrino spectrum







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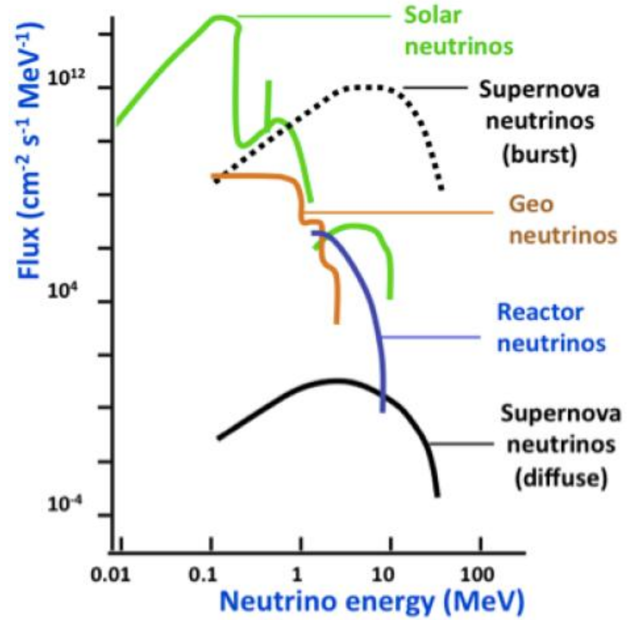
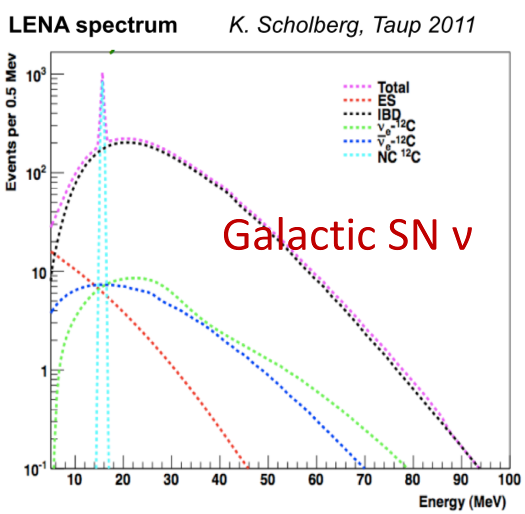
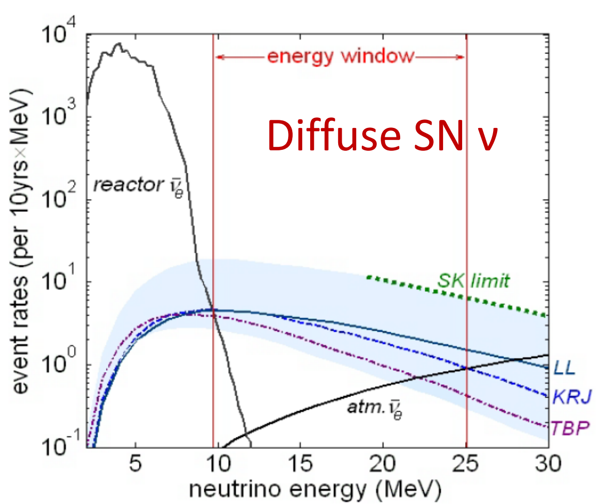
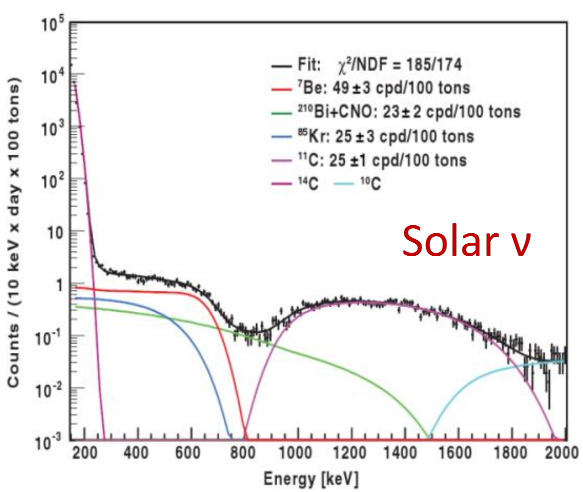
- **Diffuse supernova neutrinos:** First detection, average SN neutrino spectrum
- **Solar neutrinos:** ^{7}Be precision measurement: 5400events/day $\rightarrow$ small time fluctuations, CNO + pep, MSW effect
- **Atmospheric neutrinos:** Precise measurement of Δm_{23}^2, θ_{23}, potentially mass hierarchy
- **Indirect dark matter search:** Via abundances in neutrino spectrum, sensitive to masses ≈10-100MeV



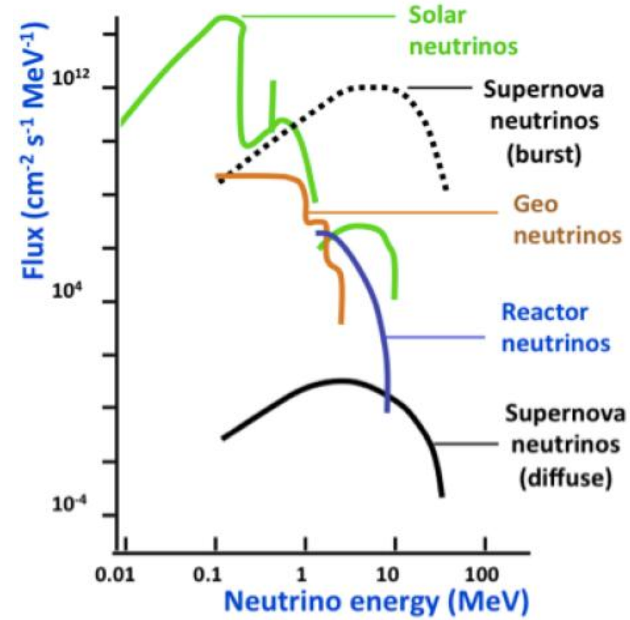


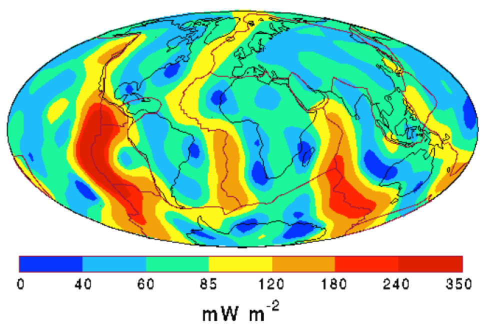


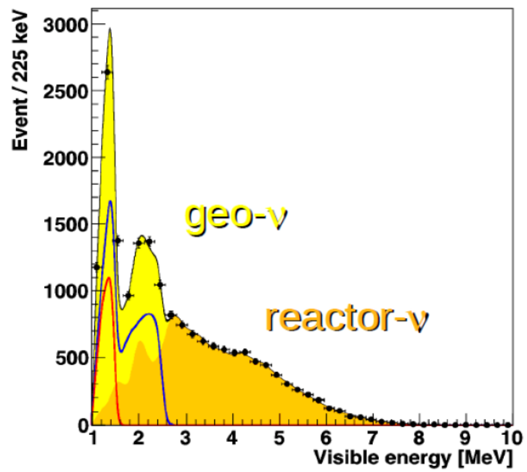


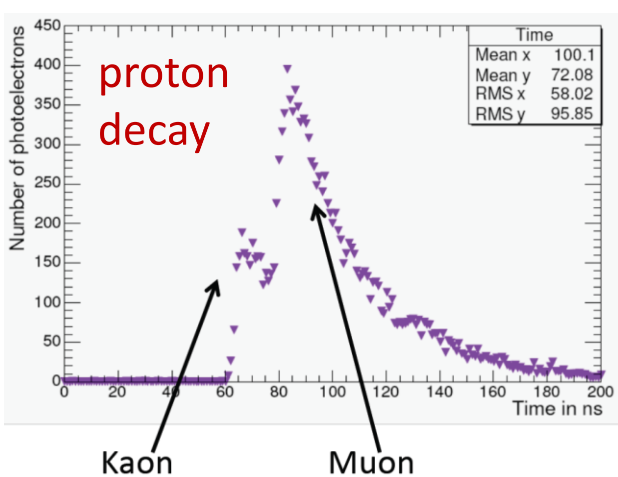
Physical goals: Natural sources

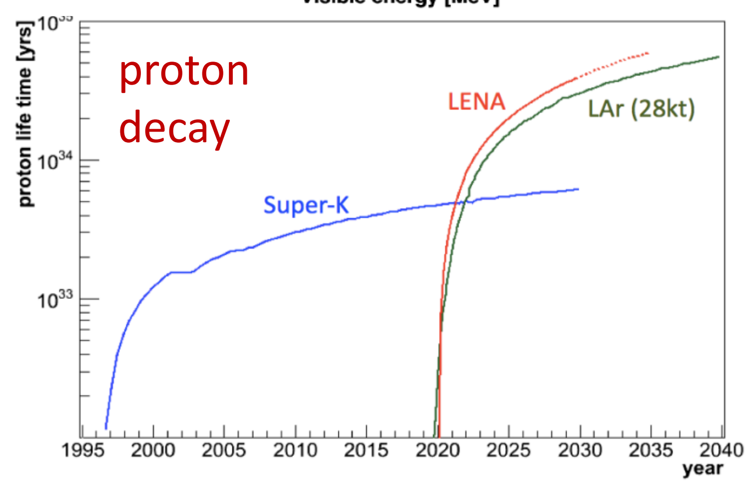
- **Geoneutrinos:** Determine U/Th decay contribution to earth heat production to 1%, ratio of U/Th contribution to 5%
- **Proton decay:** High detection efficiency (≈68%) for $p \rightarrow K^{+}\bar{\nu}$ decay channel → $\tau_{p,partial} > 4 \cdot 10^{34}$ years (90% C.L.) for 10years no events observed





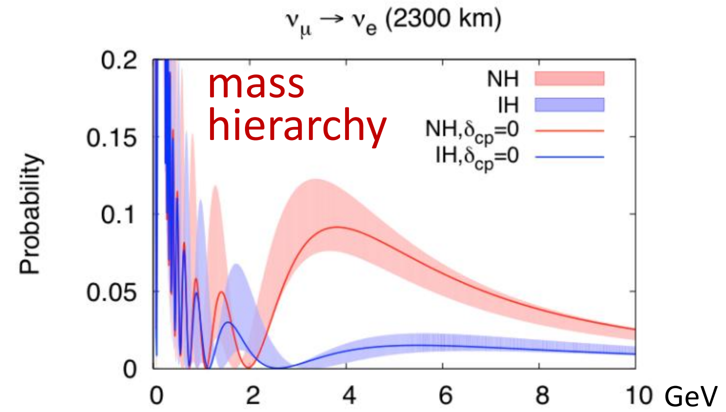


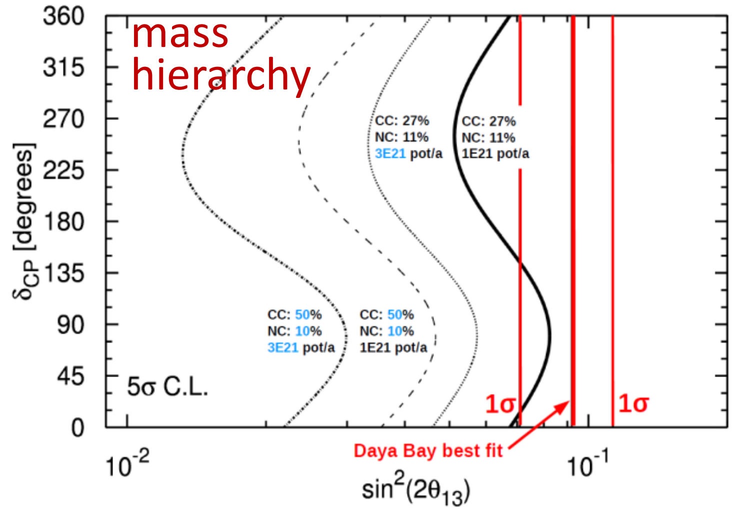




Physical goals: Artificial sources

- **Conventional ν_μ beam** CERN-Pyhäsalmi (2300km, maximum at 4-5GeV):
  - Mass hierarchy with > 5σ in 10 years, precision measurement of θ_{13}+ θ_{23}, possibly δ_{CP}





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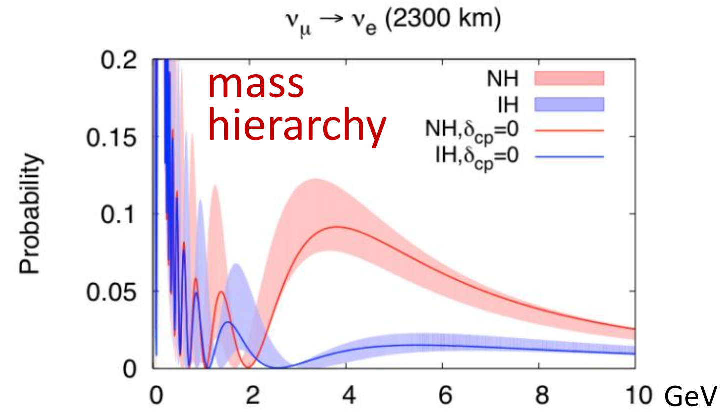
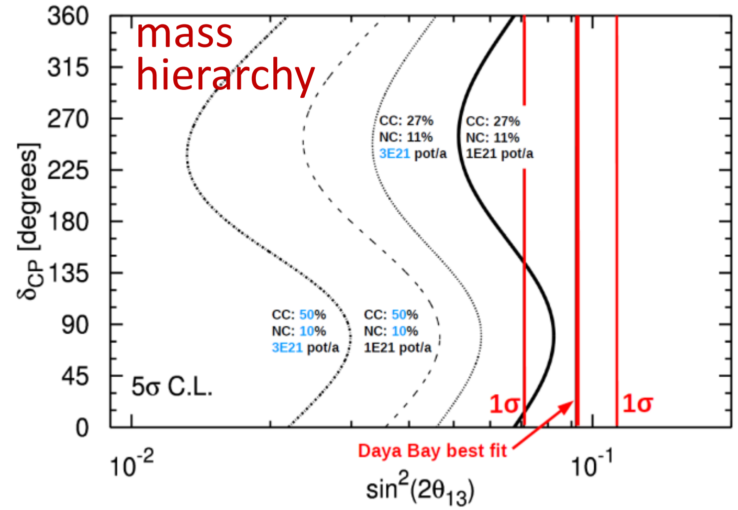
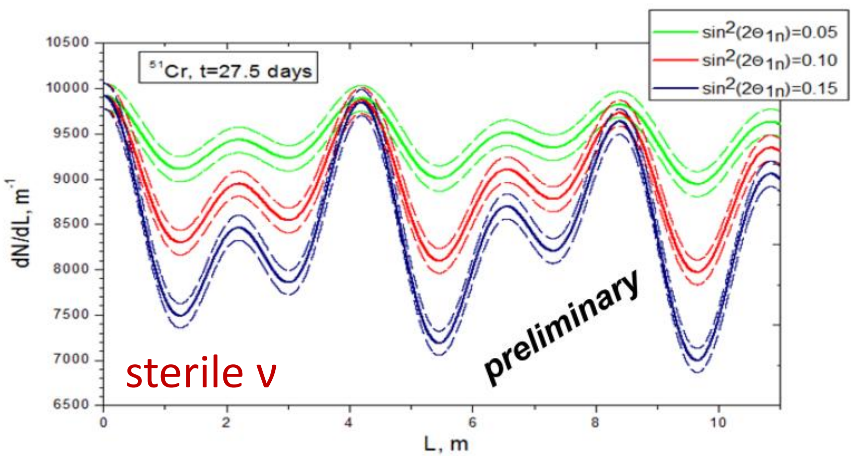
- **Electron capture neutrino source**:
  Sterile neutrinos:
  ^{51}Cr 5MCi 55days ⟶ $\sin^2(2\theta_{14})$ < $7\cdot10^{-3}$ with 90%C.L.
  $10\cdot55$days ⟶ < $2.2\cdot10^{-3}$
  θ_{13}







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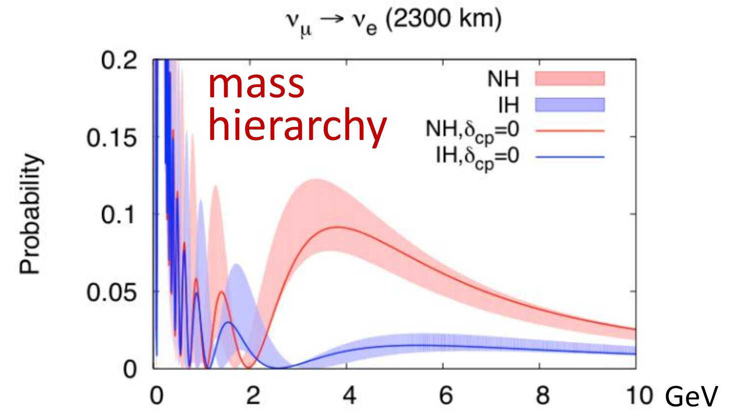
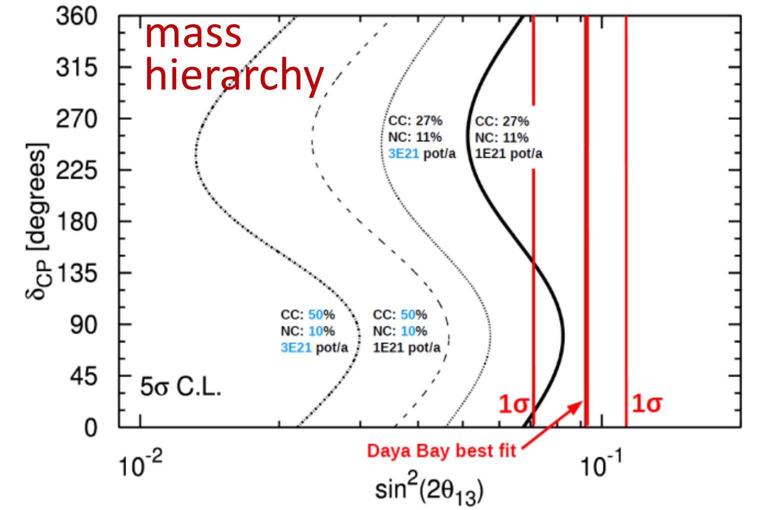
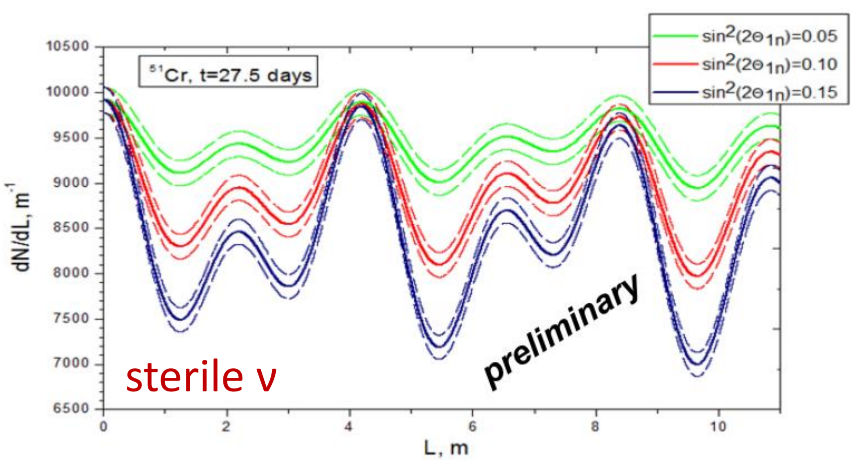
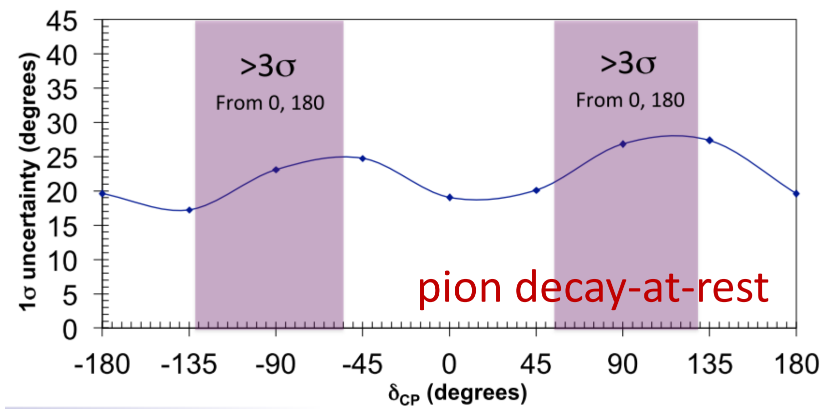
  θ_{13}
- **Pion decay-at-rest:**
  δ_{CP}: 10 years → 42% coverage with > 3σ

- **Reactor antineutrinos** (Fréjus site):
  Δm_{12}^2 ≈1%, θ_{12}≈10%

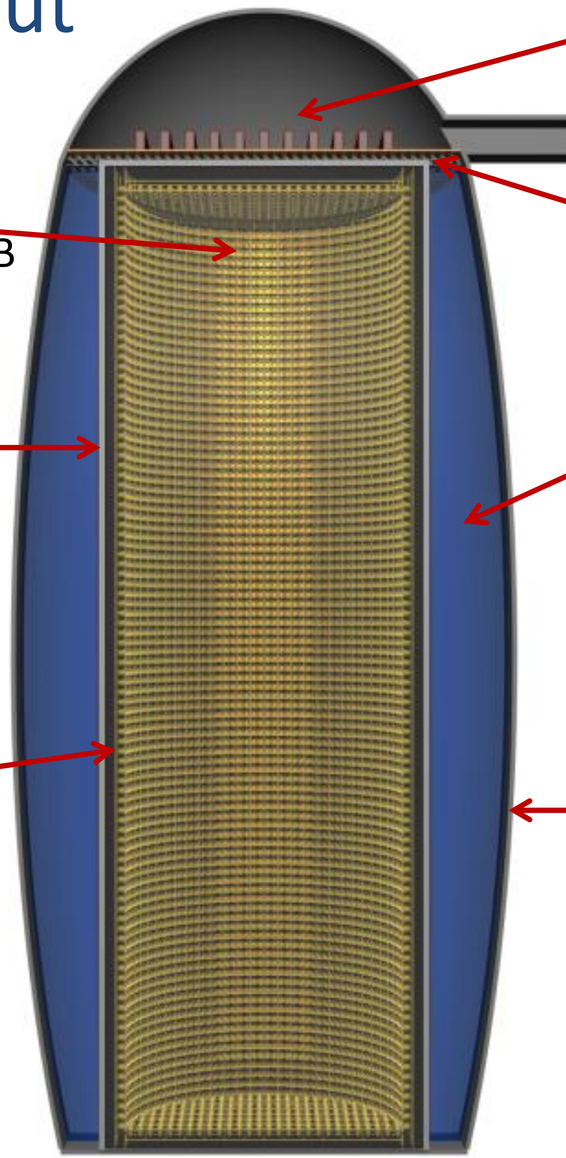








LENA detector layout



Electronics hall
20m height

Liquid scintillator
LAB + 3g/l PPO + 20mg/l bis-MSB
Active volume: 50.8kt

Top muon veto
Vertical muon tracking

Concrete tank
Covered with steel sheets
r = 16m, h = 100m,
wall thickness 60cm
Total mass: 69.1kt LAB

Water Cherenkov muon veto
133kt, min. thickness 2m
Fast neutron shield,
inclined muons
2000 12“-PMTs (encaps.)

PMT support structure
Inner face at r = 14m, h = 96m

30,000 Optical Modules:
Contains 12“-PMT, light
concentrator, *buffer liquid*
30% optical coverage
Optical shielding from tank

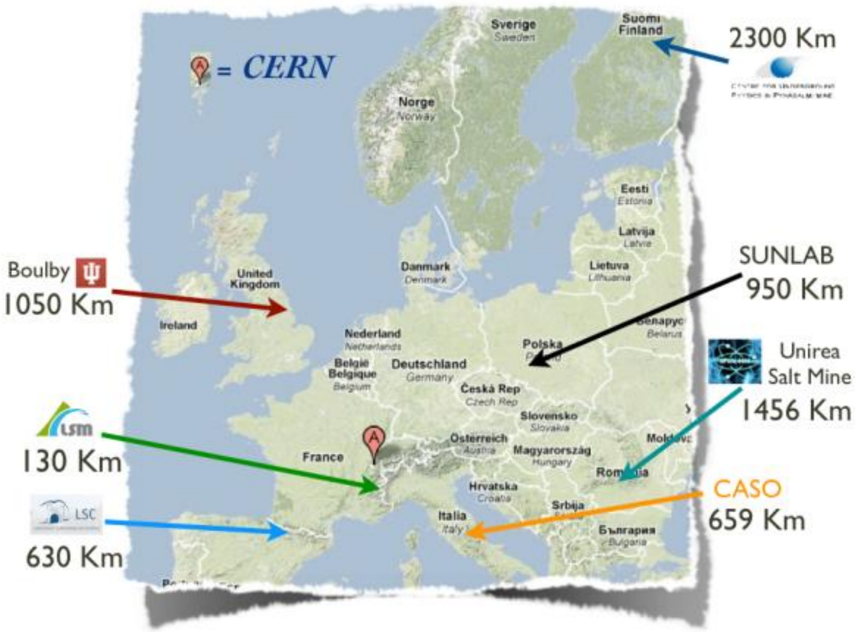
Cavern
Elliptical cross-section
from above
220,000m^3

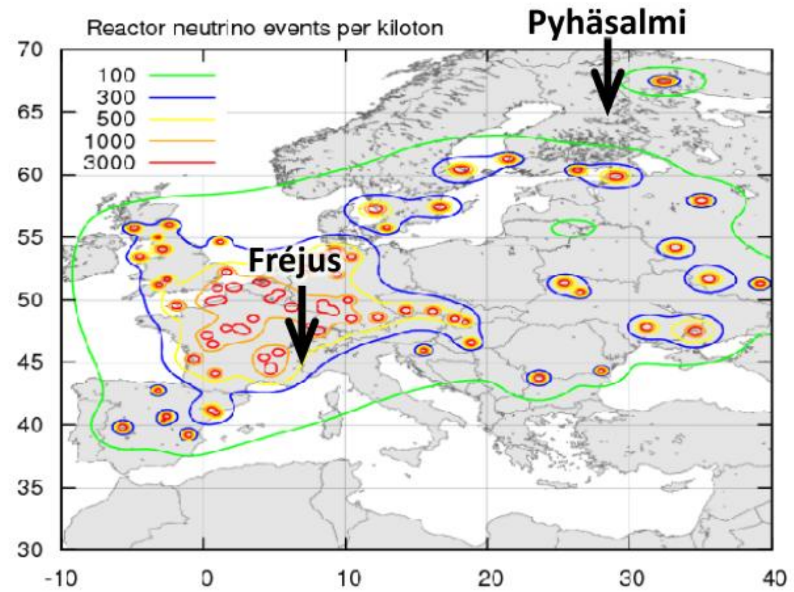
Rock overburden: 4000 mwe

Detector lifetime foreseen: > 30 years

Technical demands

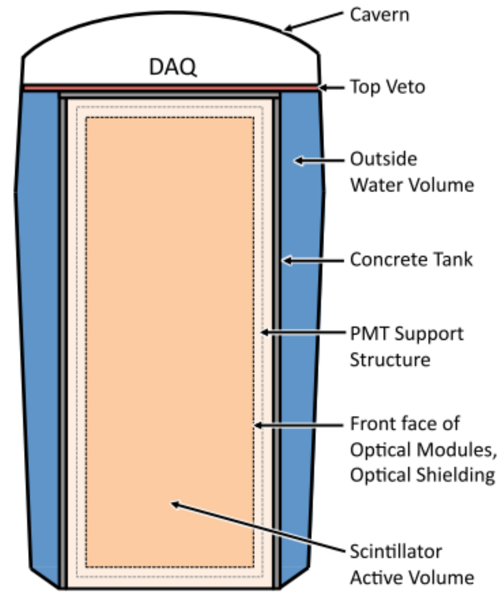
- **Site:** 4000mwe rock overburden, cavern excavation + stability, reactor neutrinos, neutrino beam ⟶ LAGUNA design study

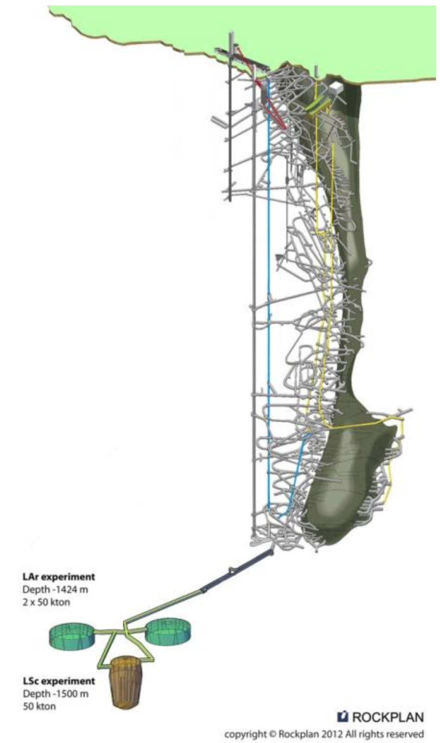




Technical demands

- **Site:** 4000mwe rock overburden, cavern excavation + stability, reactor neutrinos, neutrino beam → LAGUNA design study
- **Tank:** Shape, water shielding, buffer, optical shielding, radiopurity, chemical compatibility, cost
- **Construction:** Excavation, instrumentation, purification, filling + liquid handling





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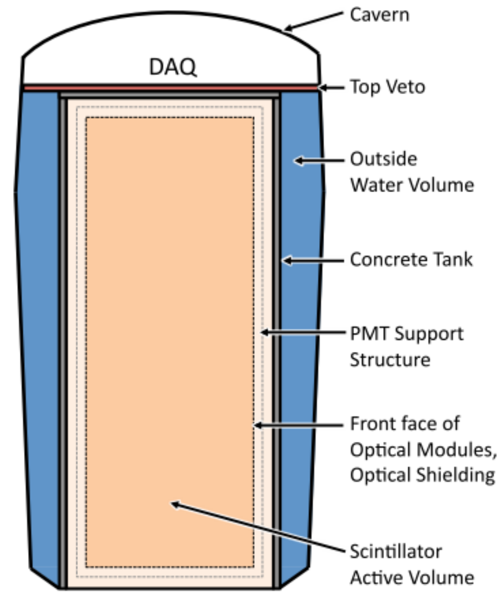

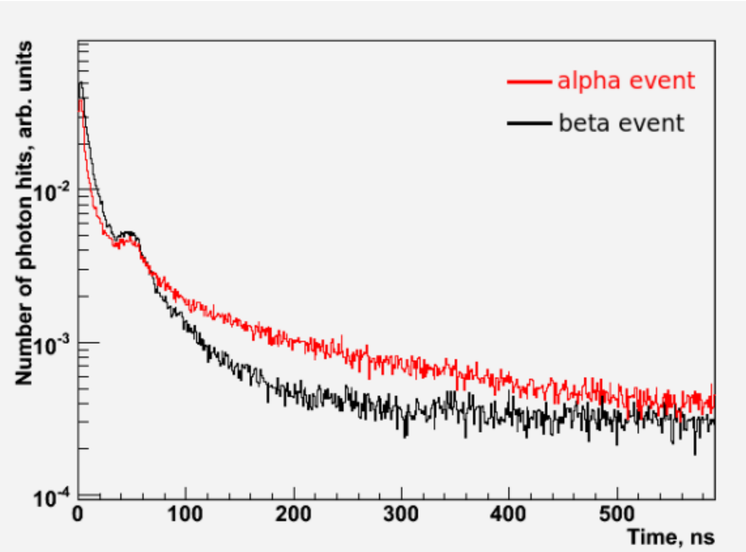

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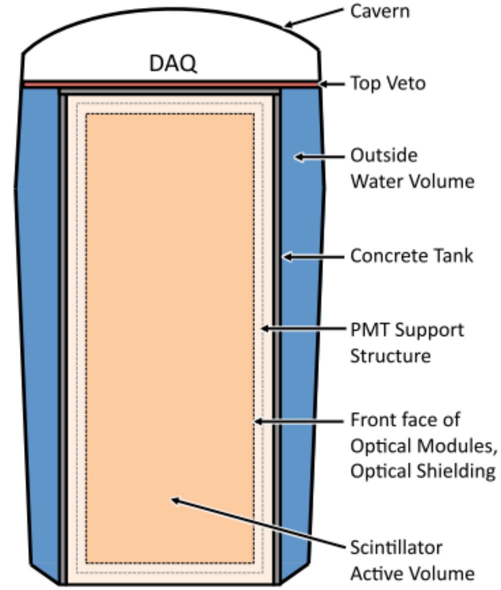
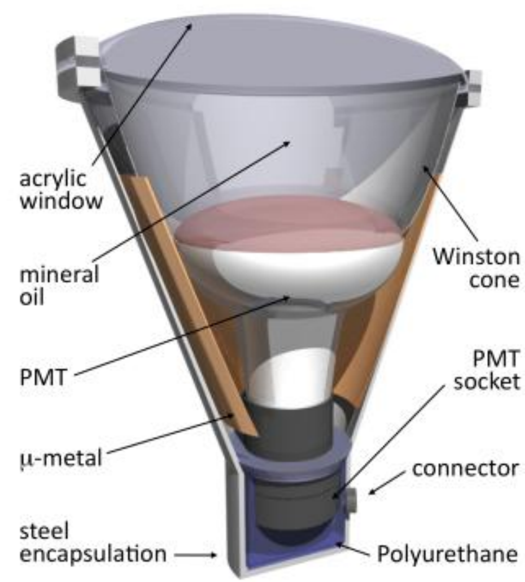
- **Photosensors:** Optical coverage, detection properties, homogeneity of p.e. yield, low background materials, pressure, chemical compatibility, lifetime, cost





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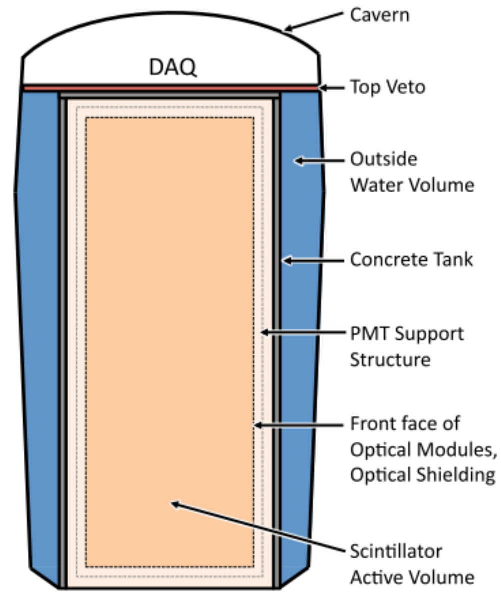
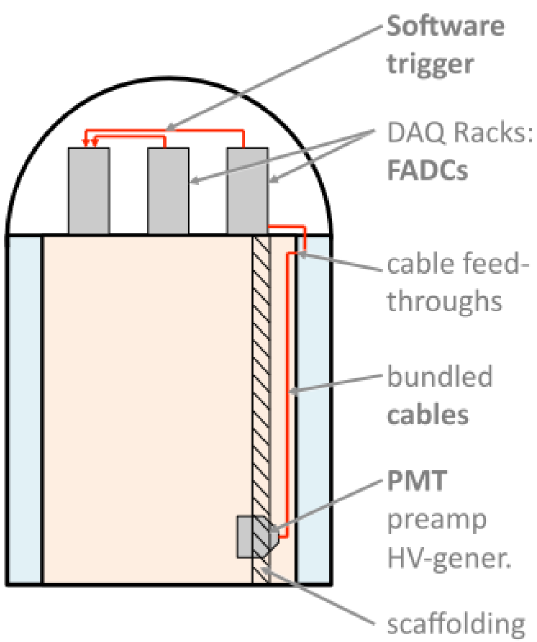
- **Photosensors:** Optical coverage, detection properties, homogeneity of p.e. yield, low background materials, pressure, chemical compatibility, lifetime, cost
- **Electronics:** Pulse shape, event rates, number of channels, cabling, sensor arrays, cost
- **Operation:** Calibration, convection, cooling, N_2-buffering, maintenance

Most issues solved, necessary R&D under way
No showstoppers





LENA White Paper published recently

Astroparticle Physics 35 (2012) 685–732

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

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Review

The next-generation liquid-scintillator neutrino observatory LENA

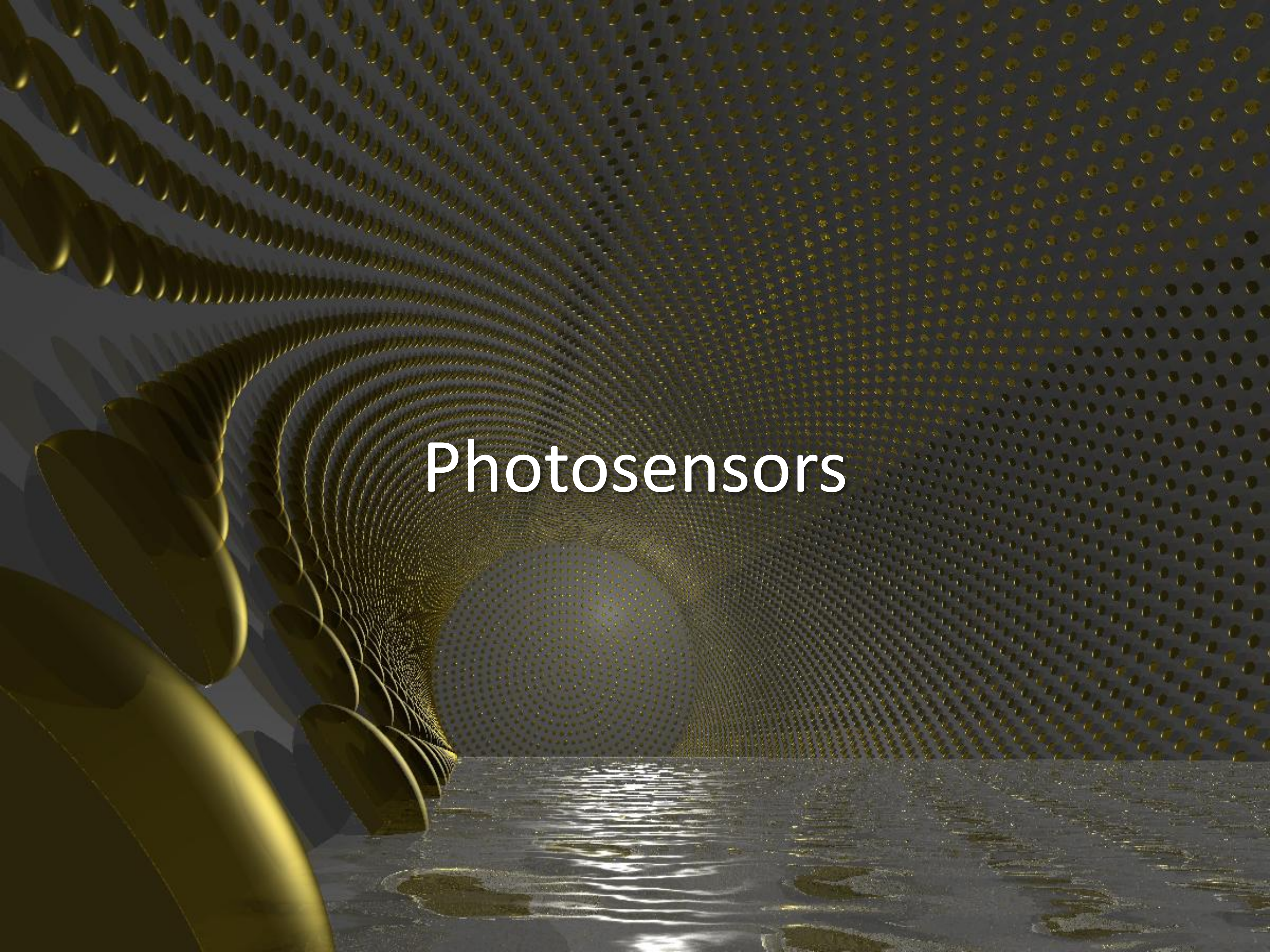
Michael Wurm[a,b,*], John F. Beacom[c], Leonid B. Bezrukov[d], Daniel Bick[b], Johannes Blümer[e], Sandhya Choubey[f], Christian Ciemniak[a], Davide D'Angelo[g], Basudeb Dasgupta[c], Alexander Derbin[h], Amol Dighe[i], Grigorij Domogatsky[d], Steve Dye[j], Sergey Eliseev[h], Timo Enqvist[k], Alexey Erykalov[h], Franz von Feilitzsch[a], Gianni Fiorentini[l], Tobias Fischer[m], Marianne Göger-Neff[a], Peter Grabmayr[n], Caren Hagner[b], Dominikus Hellgartner[a], Johannes Hissa[k], Shunsaku Horiuchi[c], Hans-Thomas Janka[o], Claude Jaupart[p], Josef Jochum[n], Tuomo Kalliokoski[q], Alexei Kayunov[h], Pasi Kuusiniemi[k], Tobias Lachenmaier[n], Ionel Lazanu[r], John G. Learned[s], Timo Lewke[a], Paolo Lombardi[g], Sebastian Lorenz[b], Bayarto Lubsandorzhiev[d,n], Livia Ludhova[g], Kai Loo[q], Jukka Maalampi[q], Fabio Mantovani[l], Michela Marafini[t], Jelena Maricic[u], Teresa Marrodán Undagoitia[v], William F. McDonough[w], Lino Miramonti[g], Alessandro Mirizzi[x], Quirin Meindl[a], Olga Mena[y], Randolph Möllenberg[a], Valentina Muratova[h], Rolf Nahnhauer[z], Dmitry Nesterenko[h], Yuri N. Novikov[h], Guido Nuijten[aa], Lothar Oberauer[a], Sandip Pakvasa[s], Sergio Palomares-Ruiz[ab], Marco Pallavicini[ac], Silvia Pascoli[ad], Thomas Patzak[t], Juha Peltoniemi[ae], Walter Potzel[a], Tomi Räihä[k], Georg G. Raffelt[af], Gioacchino Ranucci[g], Soebur Razzaque[ag], Kari Rummukainen[ah], Juho Sarkamo[k], Valerij Sinev[d], Christian Spiering[z], Achim Stahl[ai], Felicitas Thorne[a], Marc Tippmann[a], Alessandra Tonazzo[t], Wladyslaw H. Trzaska[q], John D. Vergados[aj], Christopher Wiebusch[ai], Jürgen Winter[a]

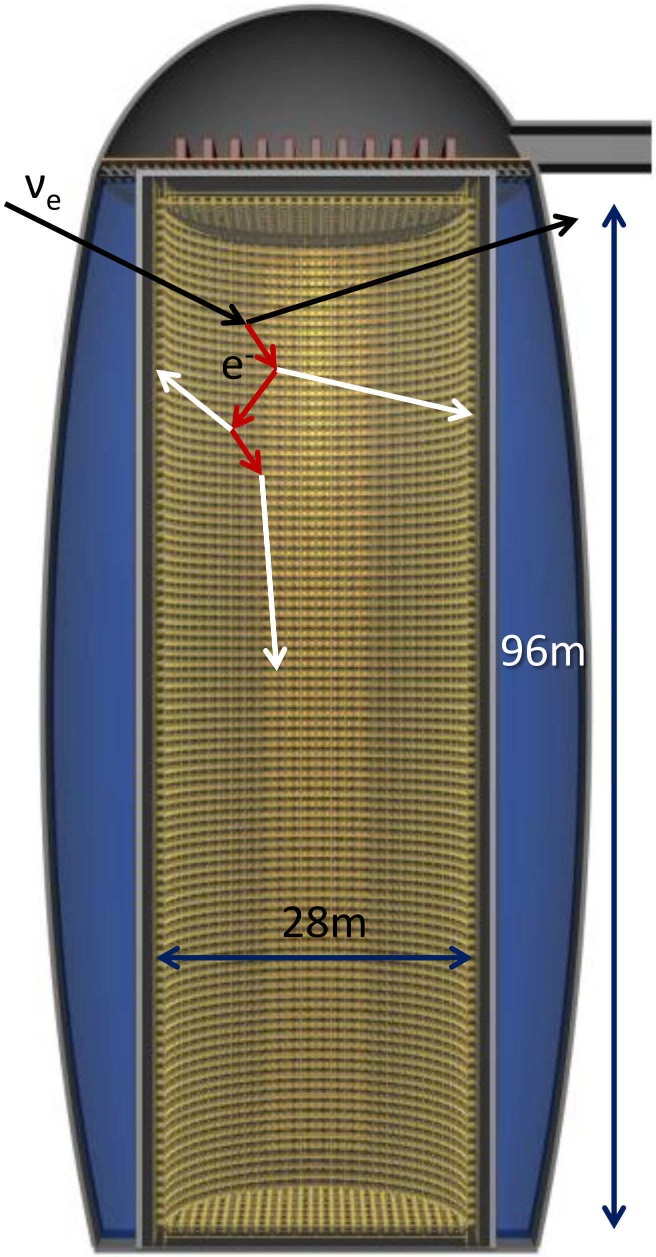
- More information can be found in the LENA White Paper
- Watch out, already some changes: e.g. physical goals (mass hierarchy, pion decay-at-rest), concrete tank, buffer within optical module, simulations of pressure encapsulation

→ Recent talks

e.g. Neutrino12, Lothar Oberauer, "Future liquid scintillator detectors"

Photosensors





Which demands result from our physics agenda?

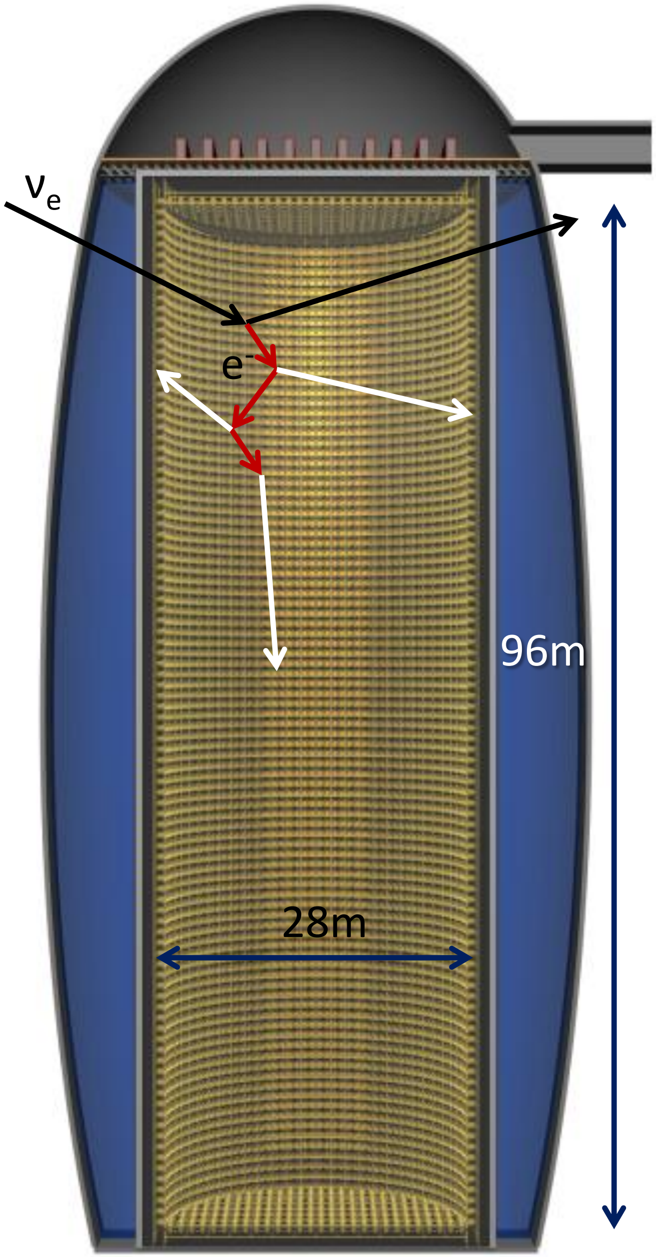
- Event detection in liquid scintillator detectors:

  Neutrino scatters off electron

  → Electron freed

  → Loses kinetic energy via excitation of scintillator molecules

  → Emit light at deexcitation



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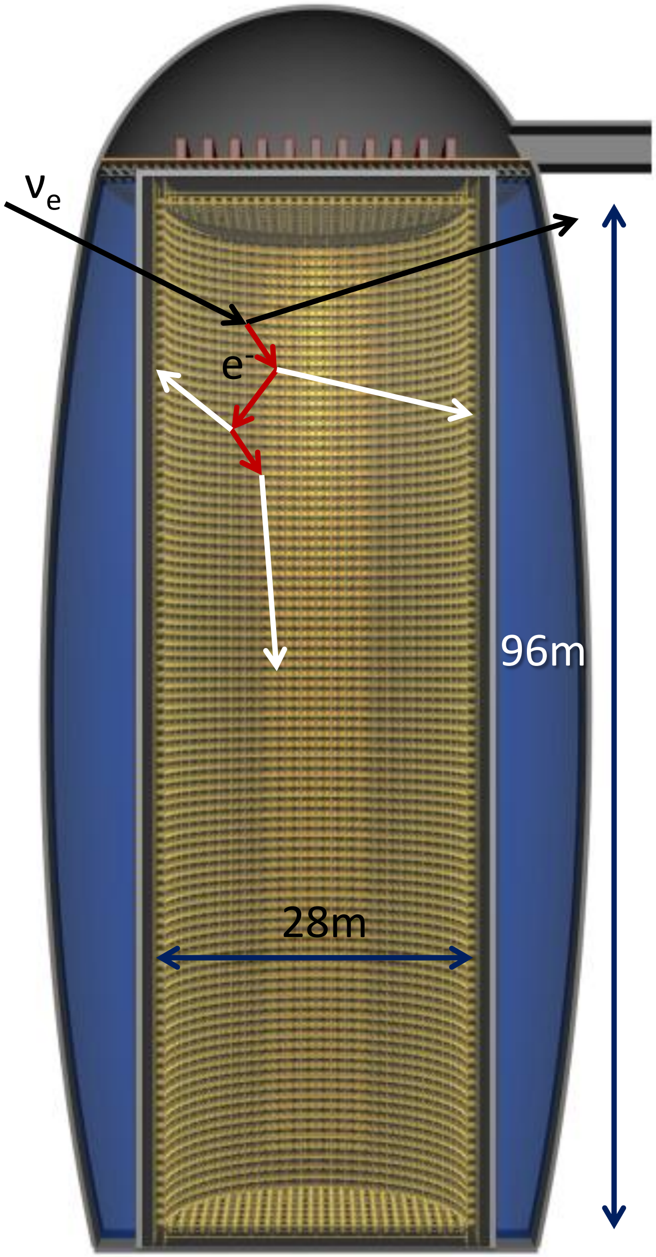
- Low interaction cross-section

  → Big active volume

  → Big surface (9700m²)

Sensor requirements:

- sensitive around 420nm
- pressure-withstanding, long-term reliability
- low price/detector area



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- Low interaction cross-section
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- Deposited energies: 200keV - ≈20GeV
  → 700 - $60 \cdot 10^6$ photons arriving at photosensor surface
- Low energies:
  Only energy of event available to distinguish neutrino sources
- High energies (e.g. neutrino beam):
  Also directionality

Sensor requirements:

- sensitive around 420nm
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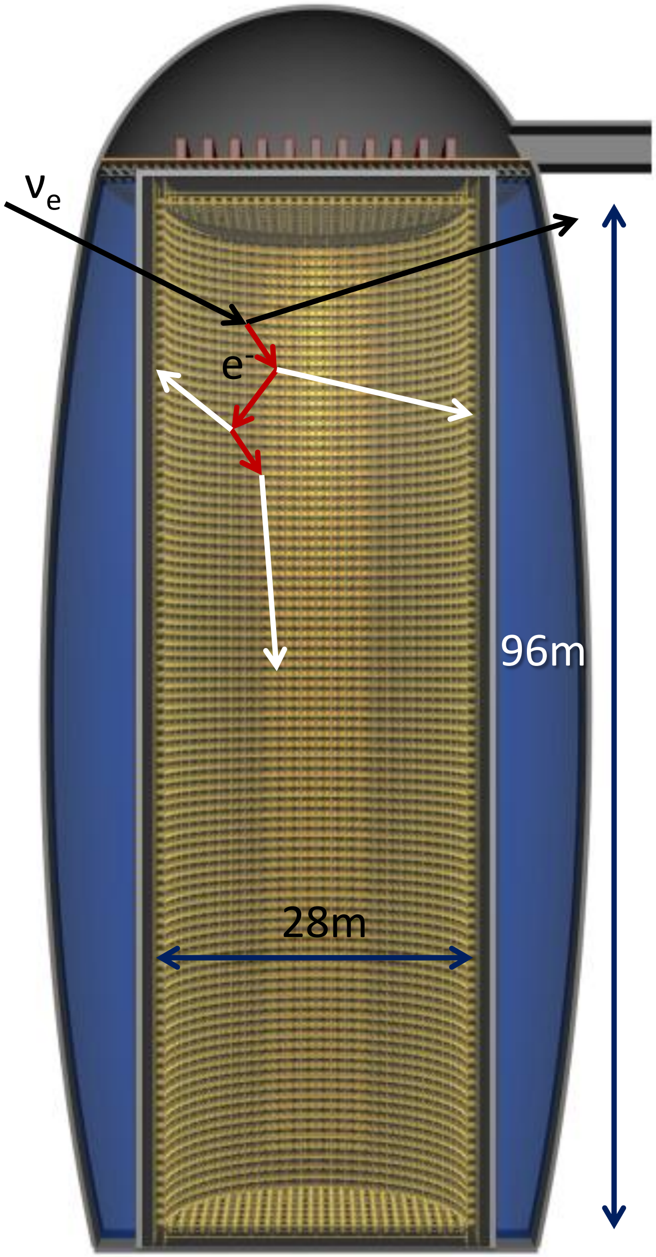
- single photon detection, high detection efficiency, large dynamic range
- good energy resolution
- low fake detections: dark count, afterpulsing good time resolution



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  Also directionality
- Background (radioactivity inside + outside of detector, atmospheric muons, …); neutrino beam
  → Event reconstruction

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- low radioactivity

How can we obtain limits for the sensor requirements?

- First estimate through comparison with previous liquid scintillator experiments (Borexino, KamLAND, DoubleChooz)
- Improve values of limits via geant4 Monte Carlo simulations
  - Determine influence of sensor properties on overall detector behavior
  - If detector properties needed to achieve physics goals are known $\longrightarrow$ can infer demands on sensor

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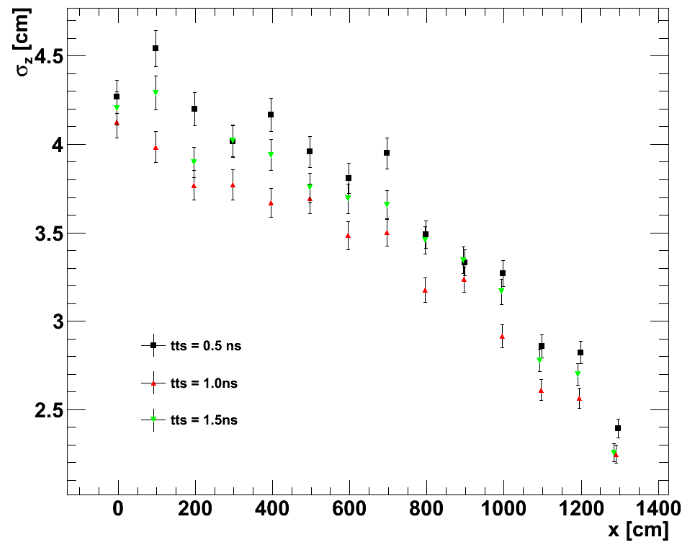
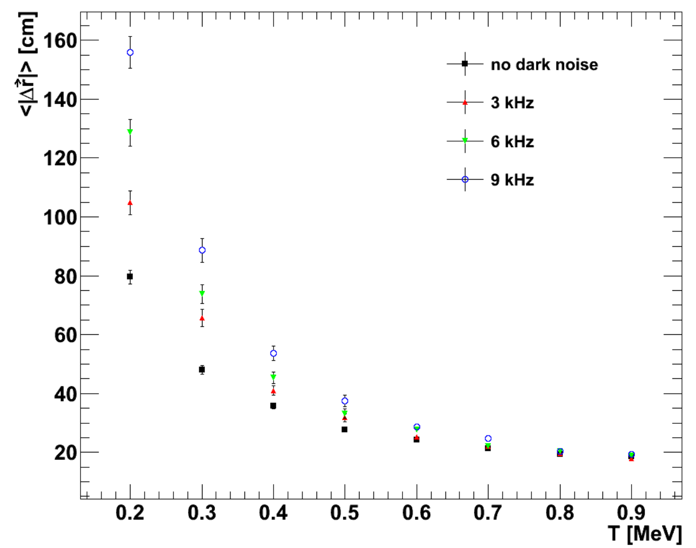
- Improve values of limits via geant4 Monte Carlo simulations
  - Determine influence of sensor properties on overall detector behavior
  - If detector properties needed to achieve physics goals are known → can infer demands on sensor

- MC studies in progress, first results:
  - Position and energy resolution (Dominikus Hellgartner)
    - Timing uncertainty:
      - First simulations, still fighting some problems with small timing uncertainties
      - First impression: no big influence
    - Dark Noise:
      - No big influence for energies around 1MeV or bigger
      - For 200keV position + energy resolution ≈30% worse
  - α/β-discrimination (Randolph Möllenberg)
    - Dark Noise:
      - Strong influence on efficiency
    - Late Pulses + Fast Afterpulses
      - Negligible effect
    - Winston Cones (50° opening angle)
      - Improve separation by a factor of two





Property	Current limit
Timing uncertainty (single photoelectrons(spe), FWHM)	<3.0ns
Early pulses	<1%
Late pulses	<4%
Quantum efficiency @420nm	>21%
Optical coverage, using 1.75x light concentrators	30%
Dynamic range	spe→0.3pe/cm²
Gain (PMTs)	$>3\cdot10^6$
Peak-to-valley ratio (spe)	>2
Dark count	< 15Hz/cm²
Slow afterpulses (0.2-200µs)	<5%
Fast afterpulses (0-200ns)	<5%
Pressure resistance	>13bar
^{238}U content	$< 3\cdot10^{-8}$g/g
^{232}Th content	$< 1\cdot10^{-8}$g/g
^{nat}K content	$< 2\cdot10^{-5}$g/g
Lifetime	>30y

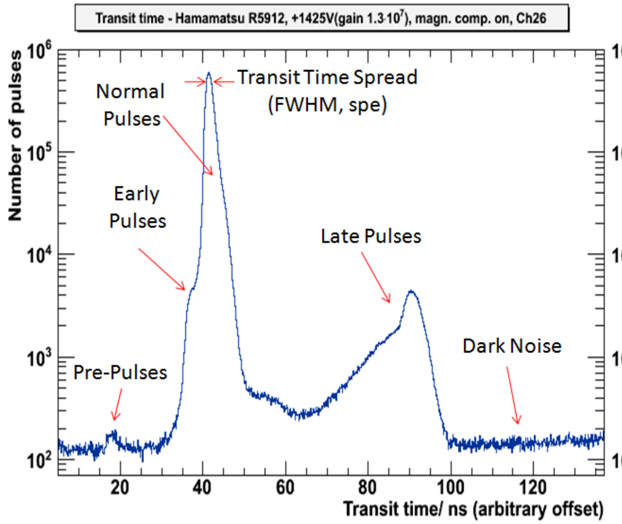
possibly higher value allowed

probably needs to be increased

order of magnitude correct for big sensors; currently simulating with different trigger layout to establish value for SiPMs

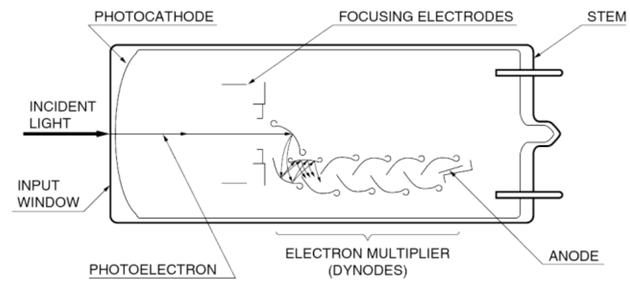
can be increased

First MC results:



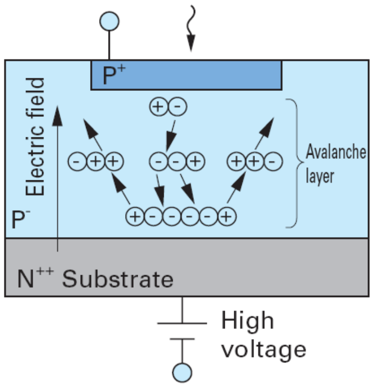
Which photosensors can fulfill the requirements?

- Photomultipliers (PMTs)
  - + Fulfill all requirements
  - → Sensor of choice at the moment



Which sensors could fulfill them?

- Si-Photomultipliers (SiPMs):
  - + Better energy resolution, time resolution, detection efficiency
  - − Dark count possibly too high
  - → Study in detail



- Hybrid detectors / New sensors
  - Crucial question: Available in high quantities in time for construction?
  - Possibly yes: QUASAR, X-HPD, HAPD, QUPID
  - Probably not: Abalone, LAPPD

Which sensors could fulfill the requirements?

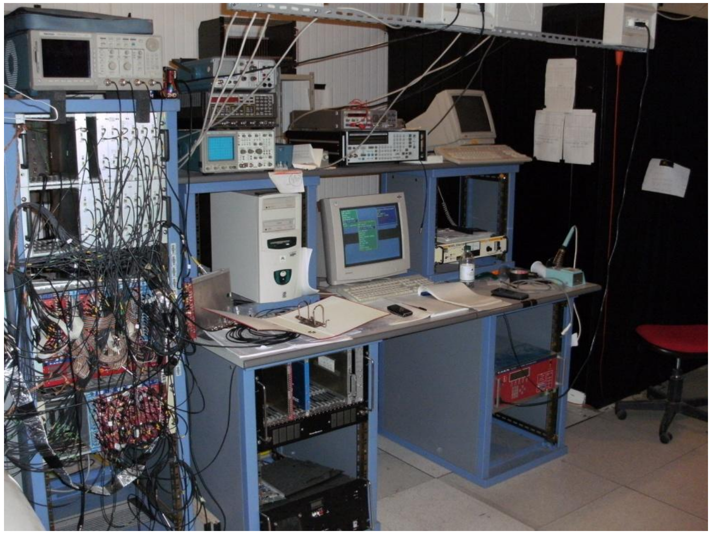
- Favored sensor at the moment: PMTs
  - New models are most promising:
    - Hamamatsu R11780 (12“)
      - good transit time spread, by now high quantum efficiency, still high afterpulsing(?), high pressure tolerance; 100 prototypes built so far
    - Electron Tubes Enterprises D784 (11“)
      - designed from scratch for good performance + high pressure tolerance, so far only dummies for pressure tests
  - Existing models:
    - Hamamatsu R6594 (5“), R5912 (8“), R7081 (10“), R7250 (20“)
    - Electron Tubes Enterprises 9823 (5“), 9354 (8“)
  - Current design: Use either 11“/12“-PMTs (40k/31k PMTs in ID) or 8“ PMTs (68k PMTs in ID)
    - 11-12“ should be at cost optimum, 8“ proven technology

D784

- Need to find out missing characteristics for all candidate sensor types + measure properties of candidate PMT series to select optimum sensor

How can we determine the missing properties?

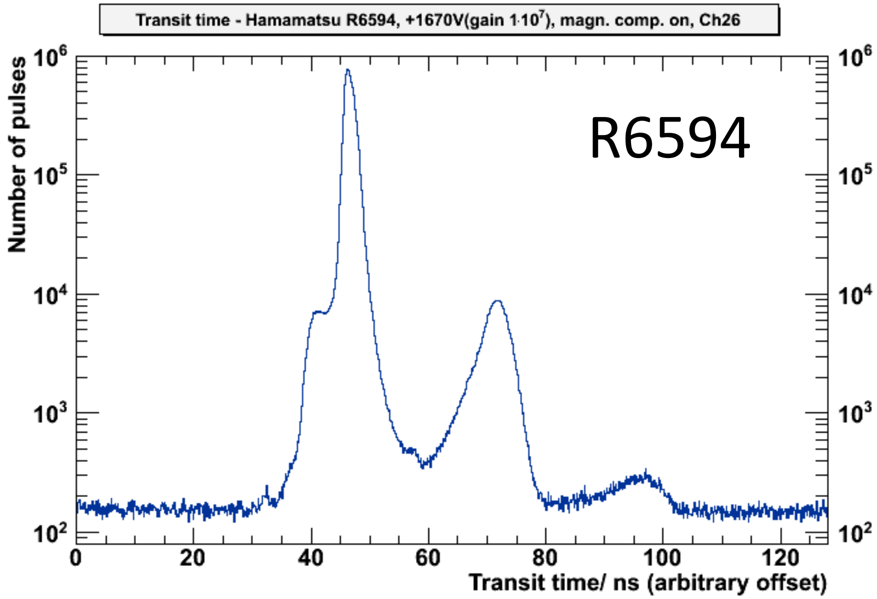
Measurements at the Borexino PMT testing facility (INFN LNGS, Italy)

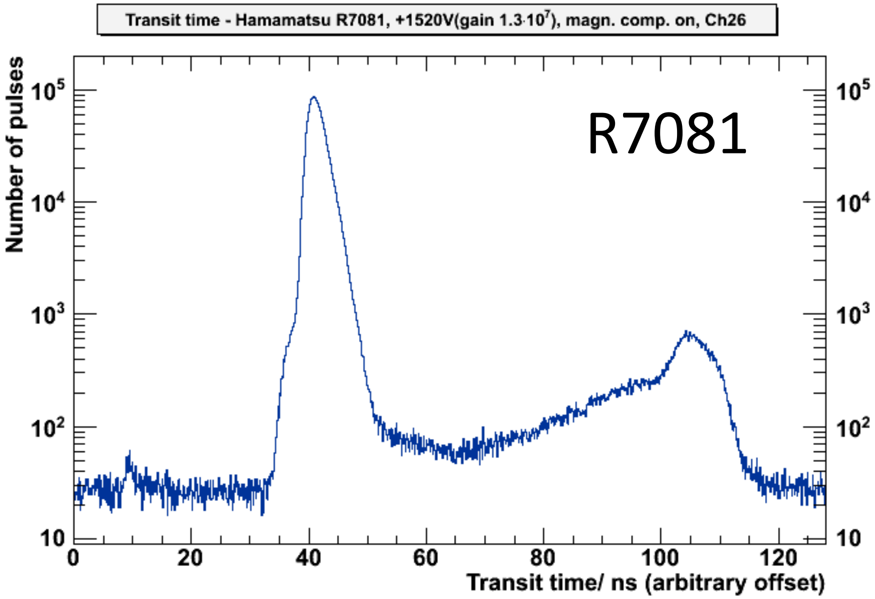


- Light source: 30ps diode laser (410nm), diffusor mounted at ceiling
- Magnetic field compensation
- Measure up to 64 PMTs simultaneously with NIM electronics

→ Transit time distribution, afterpulse time distribution, charge distribution, dark count

- Measured until now 1 sample each of:
  - Hamamatsu: R6091(3“), R6594(5“), R5912(8“) and R7081(10“)
  - ETEL: 9351(8“)

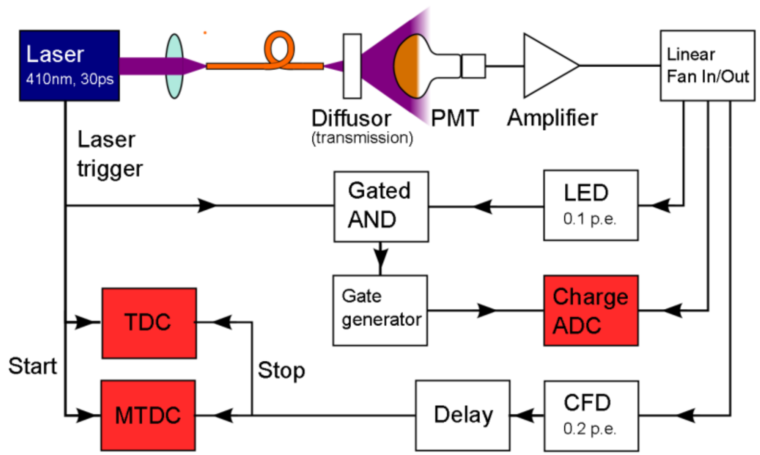




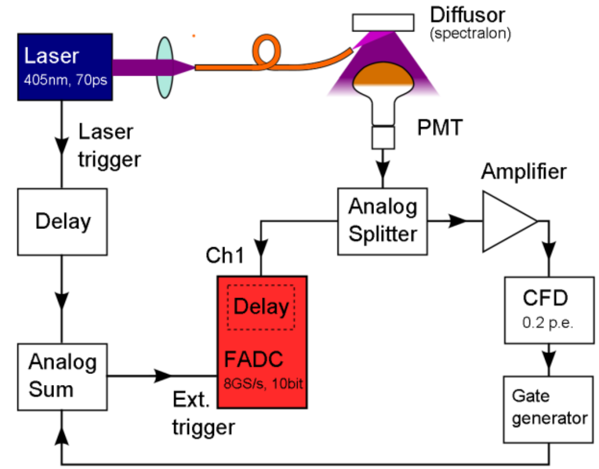
How can we determine the missing properties?

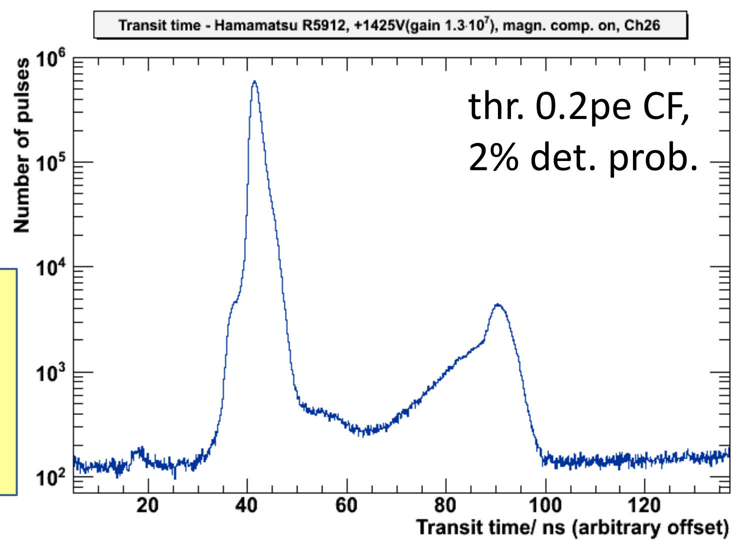
Measurements at the Munich PMT testing facility

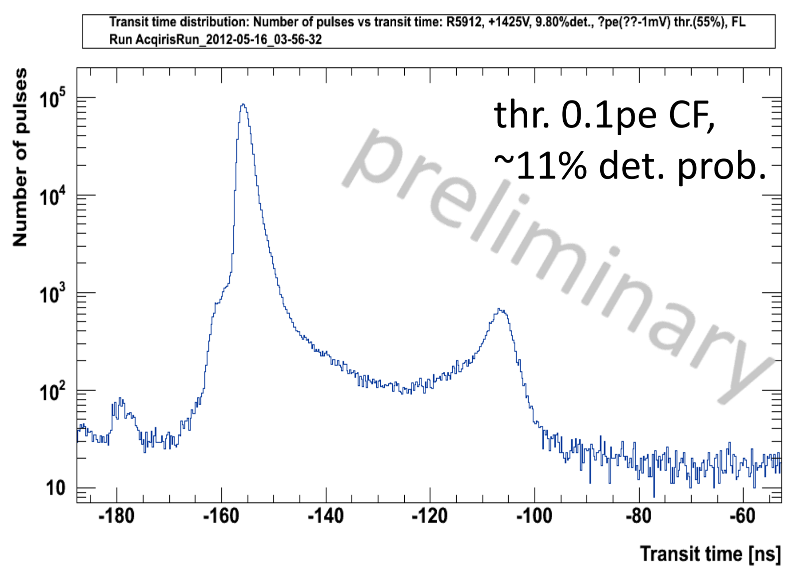
Setup PMT measurements at LNGS



Setup PMT measurements at MPI Physik







Comparison with same PMT: Hamamatsu R5912, +1425V

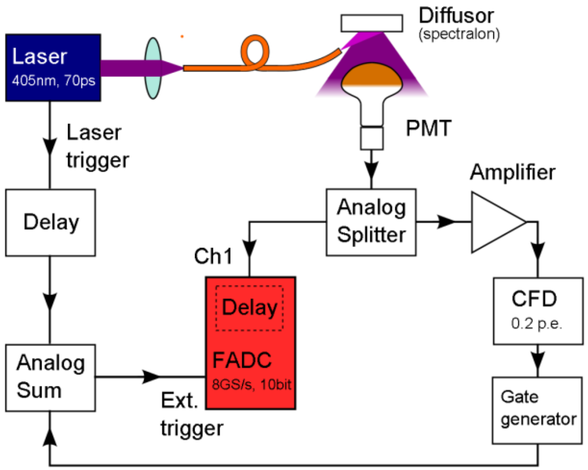
How can we determine the missing properties?

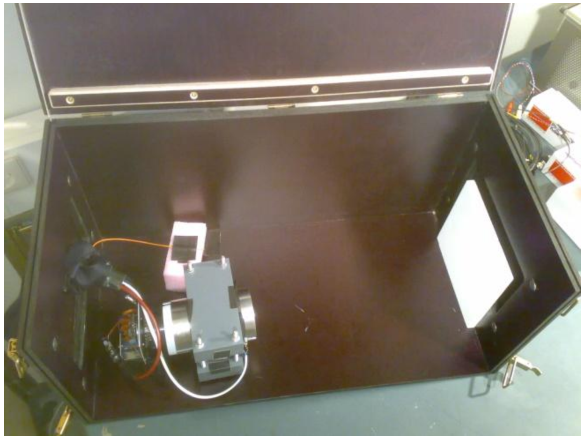
Measurements at the Munich PMT testing facility

- Key features:
  - Record waveform → greatest flexibility for measurements, offline analysis; waveform acquisiton rate up to 5kHz
  - Coincidence electronics → single photon measurements with virtually no 2-photon pulses in reasonable time + less data
  - So far can measure timing properties, dynamic range, dark count, afterpulsing + energy resolution
- Electronics works

- Next steps:
  - Migrate to larger dark box
  - Improve setup (fiber optics, transmissive diffusor, scanning, QE, more features in evaluation software…)
  - More extensive measurements of candidate sensors + light concentrators

Setup PMT measurements at MPI Physik





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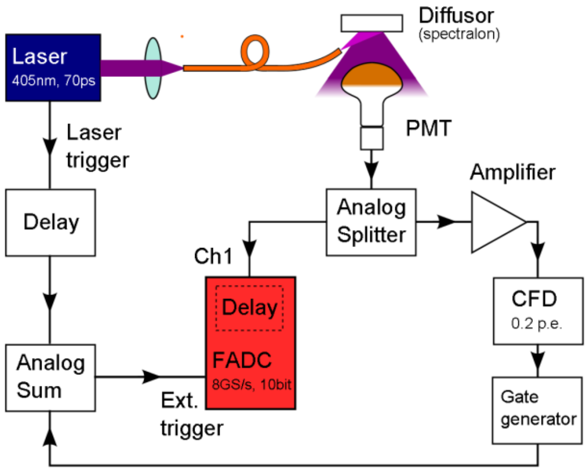
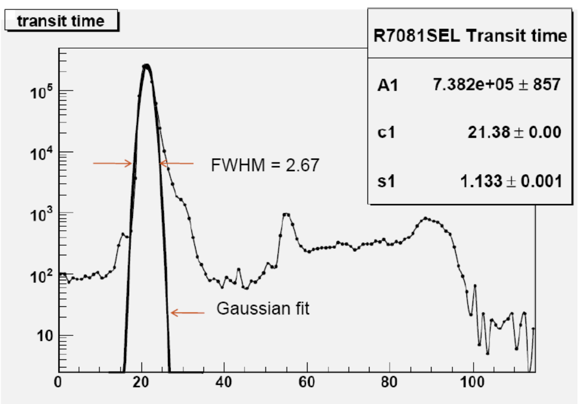
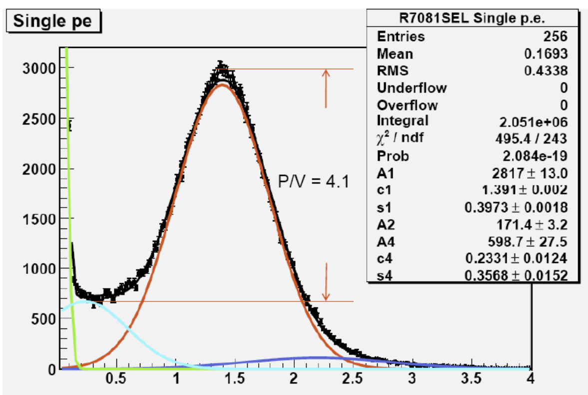
Setup PMT measurements at MPI Physik



…also:
- measurements done by Paolo Lombardi at INFN Milano of 5-10“ Hamamatsu super-bialkali PMTs (same series as tested at LNGS)

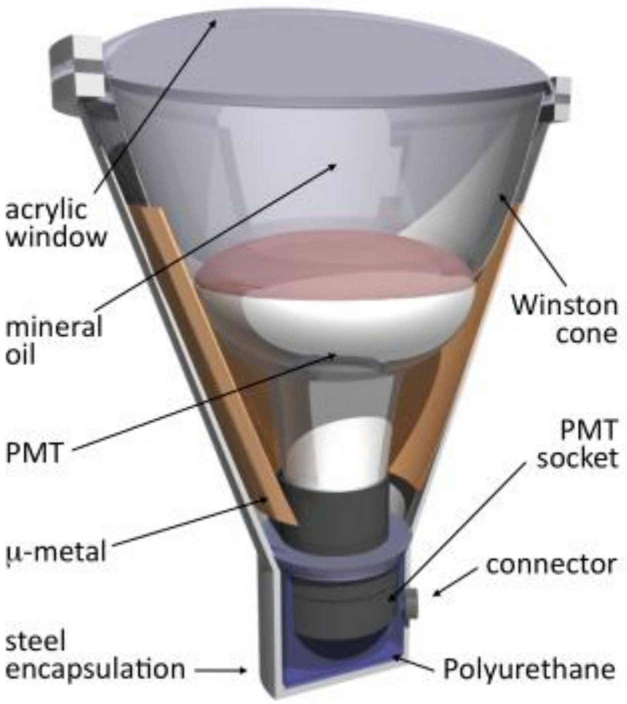




Most probably PMTs will be the photosensor for LENA

→ What components do we need for optimum performance?

- PMT
- Increase active area + limit field of view
  - → Light concentrator (Winston Cone)
- Shield PMT from earth magnetic field
  - → mu metal
- Power supply
  - → Voltage divider
- Electronics? (Amplifier, signal processing)
- Pressure
  - → Encapsulation, acrylics glass window + stainless steel housing
- During filling, tank is filled with water → conductive
  - → Cast voltage divider into insulator compatible with ultrapure water + liquid scintillator: polyurethane



Most probably PMTs will be the photosensor for LENA

→ What components do we need for optimum performance?

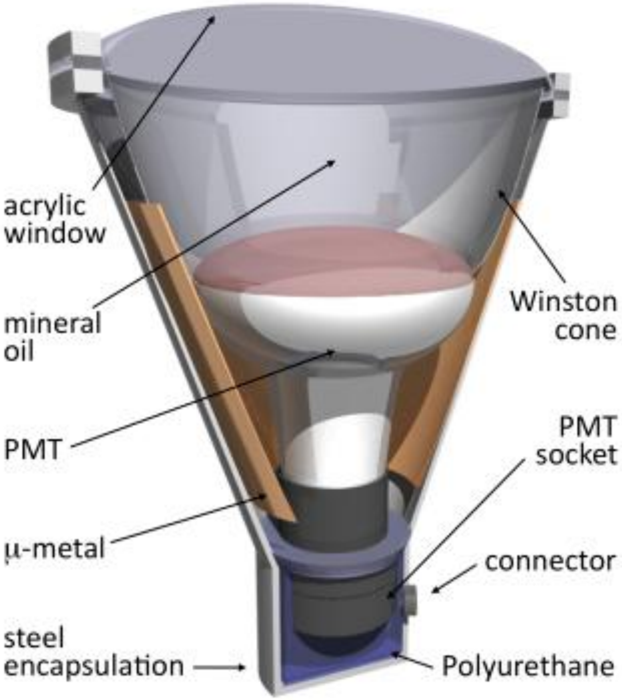
OPTICAL MODULE

- PMT
- Increase active area + limit field of view
  → Light concentrator (Winston Cone)
- Shield PMT from earth magnetic field
  → mu metal
- Power supply
  → Voltage divider
- Electronics? (Amplifier, signal processing)
- Pressure
  → Encapsulation, acrylics glass window + stainless steel housing
- During filling, tank is filled with water → conductive
  → Cast voltage divider into insulator compatible with ultrapure water + liquid scintillator: polyurethane

- Need to shield scintillator from radioactive contamination contained in the PMT's glass → layer of inactive buffer liquid between scintillator and PMTs

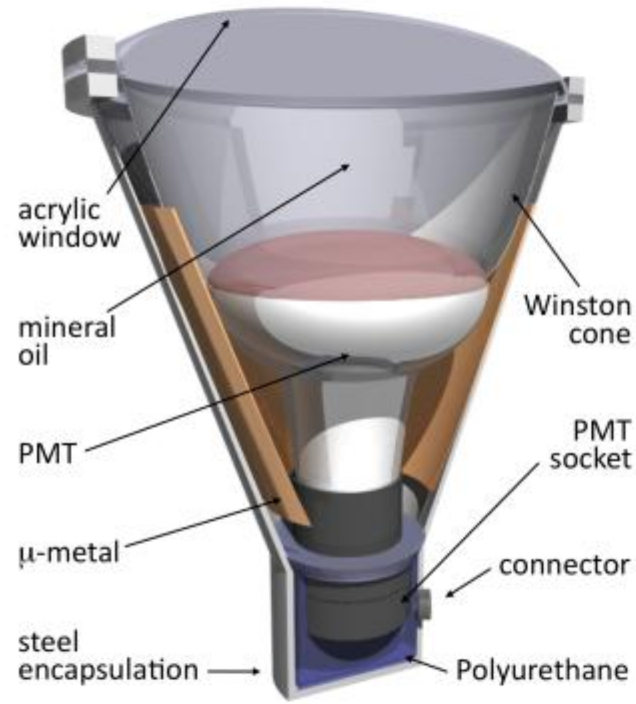
  New design: include buffer liquid into pressure encapsulation

  → Bigger active volume!

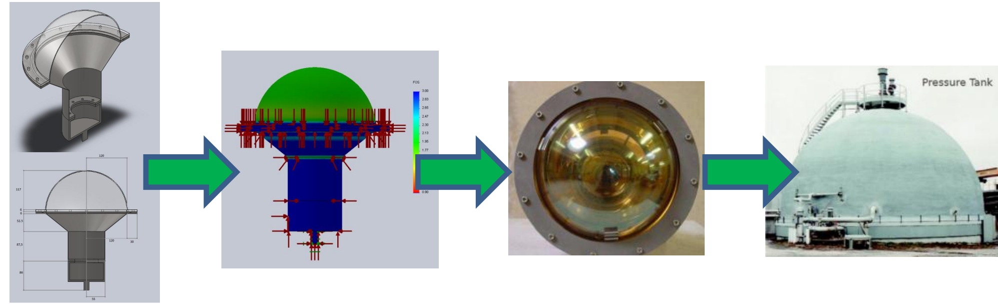


PMT optical module: Status of development

- PMT
  - Determine requirements → in progress
  - Measure properties → in progress
    - Selection of best series → to do
    - Modifications? → to do
- Pressure encapsulation
  - Design (include design of OM) → in progress
    - Simulations → in progress
      - Build prototype → to do
        - Test: pressure tank, radiopurity, long term → to do
- Light concentrator
  - Simulations → in progress
    - Build prototype → to do
      - Test:
        - Optical properties → to do
        - Material compatibility → in progress



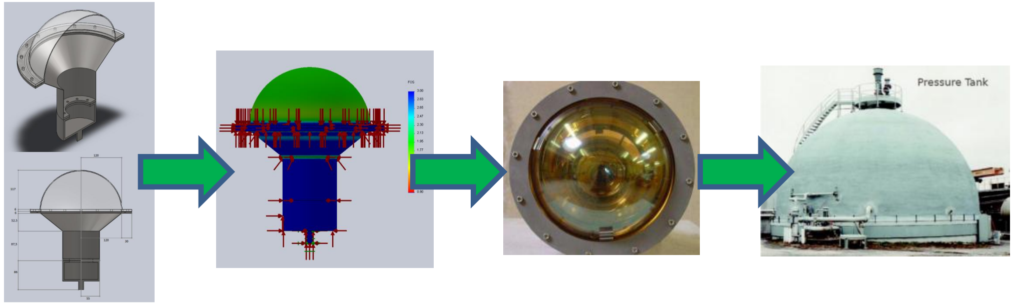
Pressure encapsulations



How to develop an encapsulation?

- *Design, pressure simulations*, build prototype, pressure tests

Pressure encapsulations



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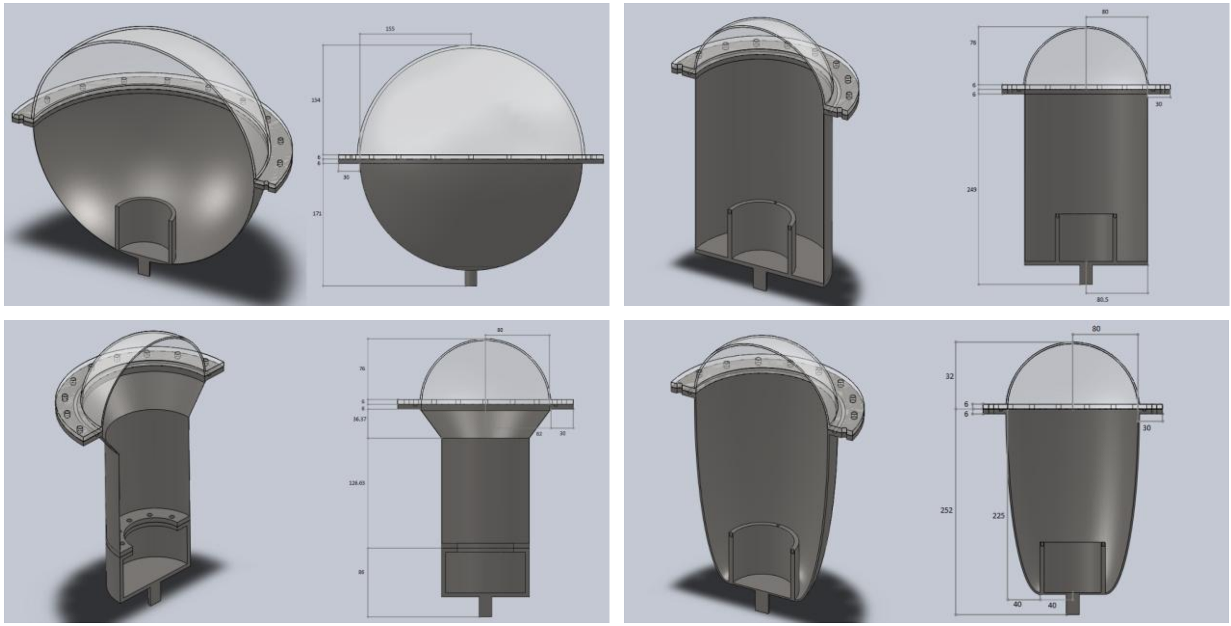
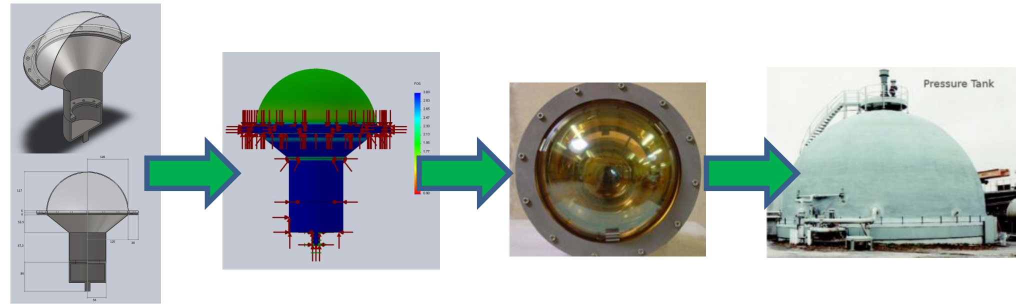
Was treated in Bachelor thesis + continuing work of German Beischler

- Created engineering drawings
  - …for different designs (spherical, conical, cylindrical, elliptical, rotated spline)
  - …for 5-10“ PMTs of Hamamatsu + ETEL



Pressure encapsulations



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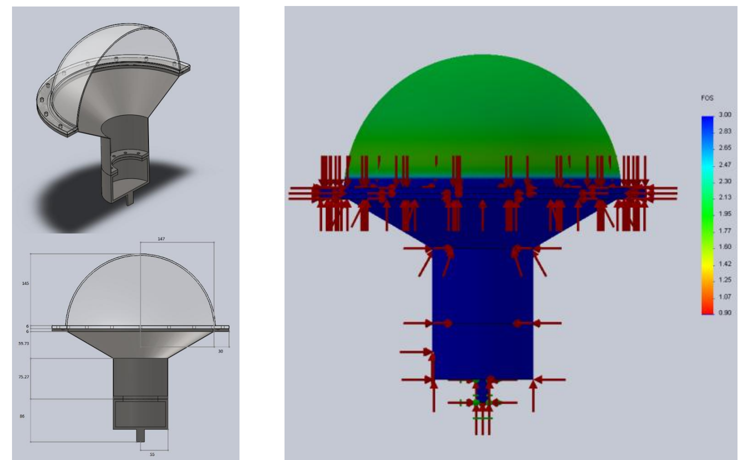
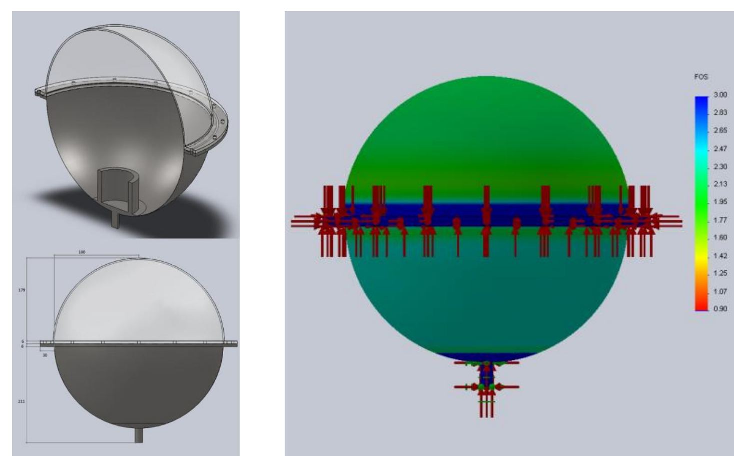
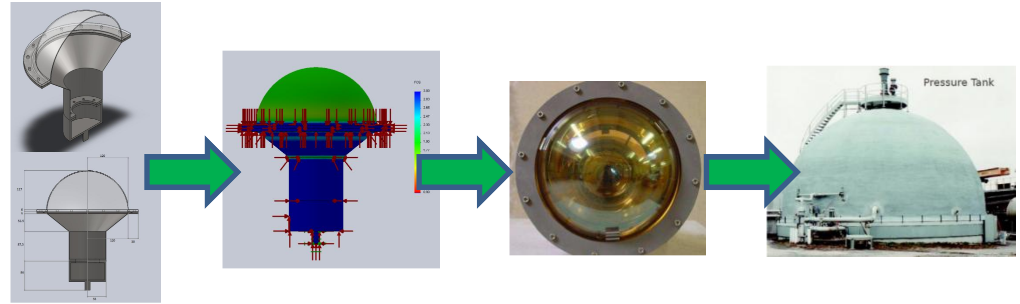
- Did first Finite Element Analysis simulations with SolidWorks to determine necessary thicknesses + weight
  - Need encapsulations due to pressure, but weight = radioactivity → keep them as thin as safety allows





Pressure encapsulations



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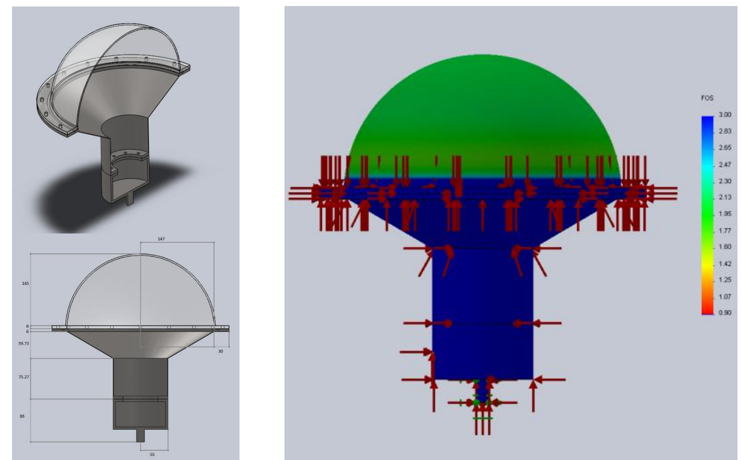
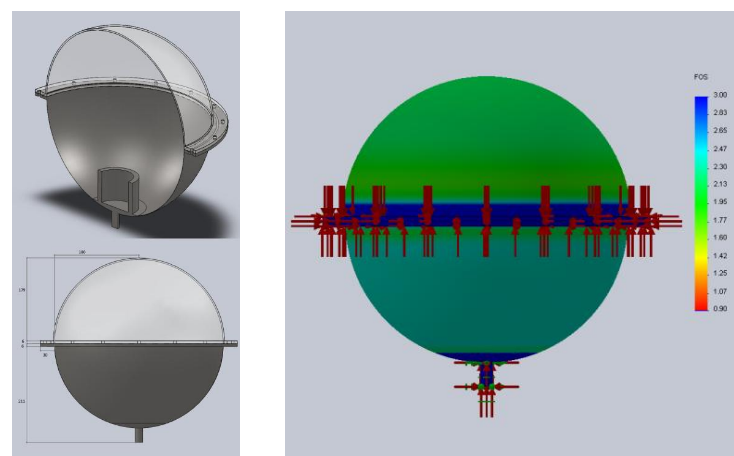
- Did first Finite Element Analysis simulations with SolidWorks to determine necessary thicknesses + weight
  - Need encapsulations due to pressure, but weight = radioactivity → keep them as thin as safety allows
- Simulations so far were still for the old optical module without the buffer liquid → have to adapt design
- Currently cross-checking results + dependence on simulation parameters and improving simulations

  → Switching from volume meshing to shell-meshing; are considering migrating from SolidWorks to ANSYS





Conclusions

LENA

… is a future 50kt liquid scintillator detector, which could provide valuable insights on neutrino properties, measure various neutrinos sources with unprecedented accuracy and set more stringent upper limits on proton decay

Detector layout in short:

Active mass 50kt, concrete tank, 32,000 12" –PMTs, buffer inside optical module
Background → 133kt water cherenkov muon veto + top muon veto, 4000mwe rock overburden, favored site at the moment Pyhäsalmi, Finland

Physics highlights:

Galactic supernova neutrinos + diffuse supernova neutrino background, geoneutrinos

Proton decay via $K^+ \bar{\nu}$:	10 years background-free → lifetime > $4 \cdot 10^{34}$ years (90% C.L.)
Mass hierarchy:	10^{21} POT → > 5σ significance
Sterile neutrinos:	^{51}Cr 5MCi 550days → $\sin^2(2\theta_{14}) < 2.2 \cdot 10^{-3}$ with 90% C.L.
δ_{CP}:	via 10 years pion decay-at-rest → 42% coverage with >3σ

Foreseen start of data taking in 2022

Conclusions

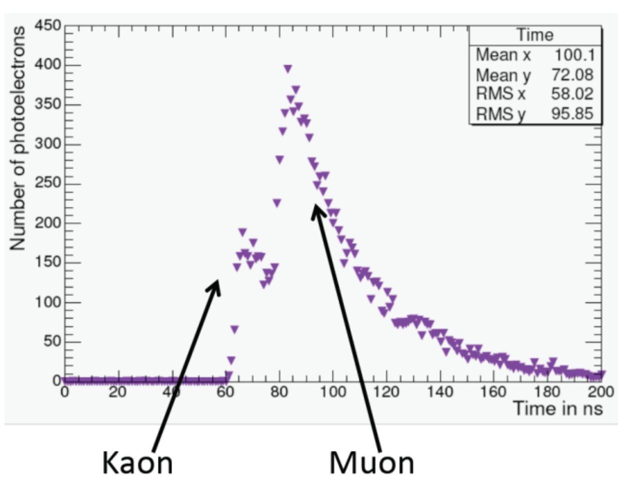
<u>Photosensors</u>

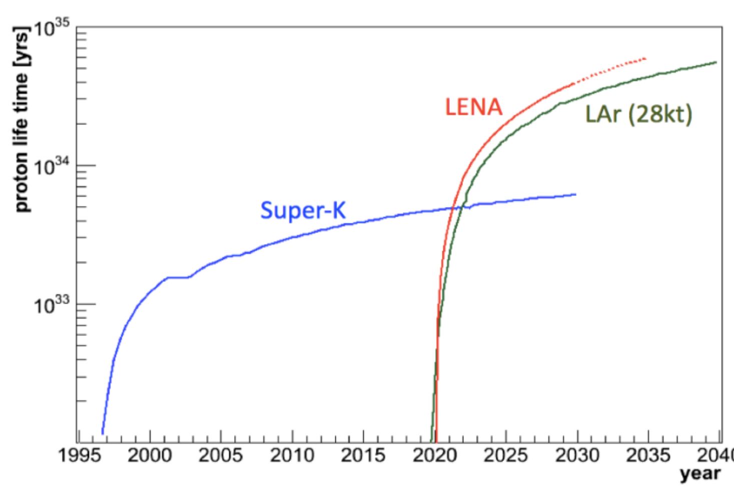
- Physics goals of LENA set demanding requirements for photosensors
- Started to quantify limits with Geant4 Monte Carlo simulations
- Measured properties for 5-10“ PMT series at LNGS + Milano
- Constructing photosensor test facility in Munich to measure missing sensor properties, first test measurements in good agreement
- So far PMTs favoured option:
  - Current standard option: Hamamatsu R11780 (12“)
  - Some other promising alternative sensors have to be tested
- Designed an optical module for PMTs consisting of light concentrator, buffer liquid, mu metal, voltage divider, pressure encapsulation
- Have completed first designs + FEA simulations of pressure encapsulations → optimize designs, cross-check simulation results
- First prototype of complete optical module in ≈ 1 year

Backup slides

$p \longrightarrow K^+ \bar{\nu}$

- LHC won't exclude complete parameter space for SUSY SM extensions
- K^+ decay channel is favored due to R parity, which is part of all SUSY theories $\longrightarrow$ parameter space left to be excluded
- We plan to improve our background rejection capability (currently 0.6 events / 500 kt ·yrs) by including the tracking capability of LENA $\longrightarrow$ 20 yrs bg-free measurement time $\longrightarrow$ exclude up to $\approx 1 \cdot 10^{35}$ yrs $\longrightarrow$ covers greatest part of SUSY extensions
- Even without a viable theory, all channels must be examined - it could well be that all current theories are wrong. This channel combines quarks from first + second family $\longrightarrow$ particularly interesting
- LENA has the highest detection efficiency + mass of currently planned detectors for this channel
- Nevertheless: will look at potential of K^0 channels in near future



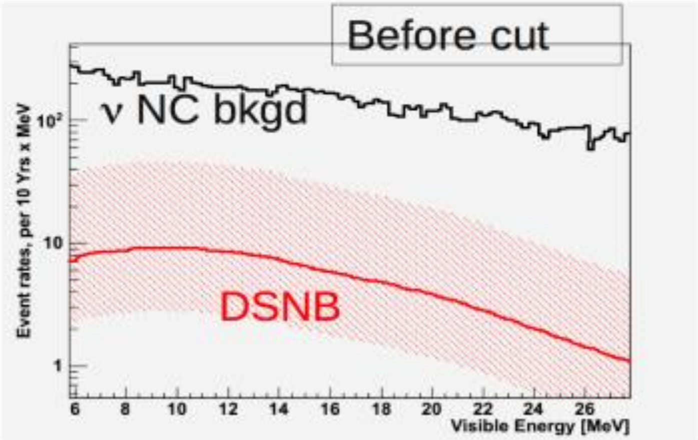


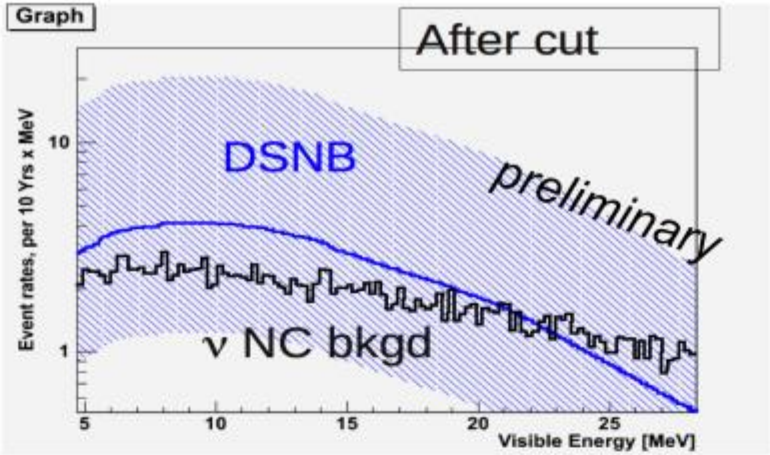
DSNB background studies

- Cosmogenic produced neutrons
  no problem if d > 4000 mwe
  < 0.2 events / year
- Cosmogenic produced beta-neutron emitter (e.g. ^{9}Li)
  no problem if d > 4000 mwe
  < 0.1 events / year
- Atmospheric neutrino CC reaction
  10 < E / MeV < 30
- **Atmospheric neutrino NC reaction** – neutron production
  data from KamLAND

n-scattering TOF exp. at MLL (Garching)

severe bg: reduction by pulse shape discrimination and/or statistical subtraction ?
Laboratory experiments indicate that a strong bg-reduction can be achieved !



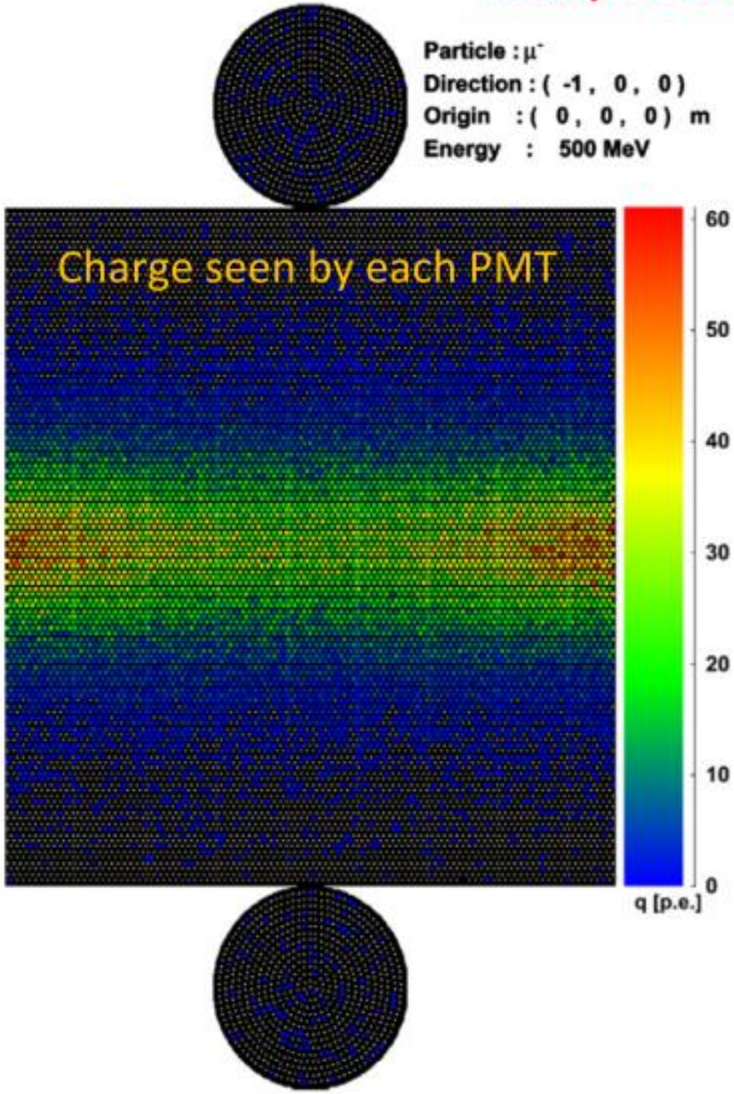


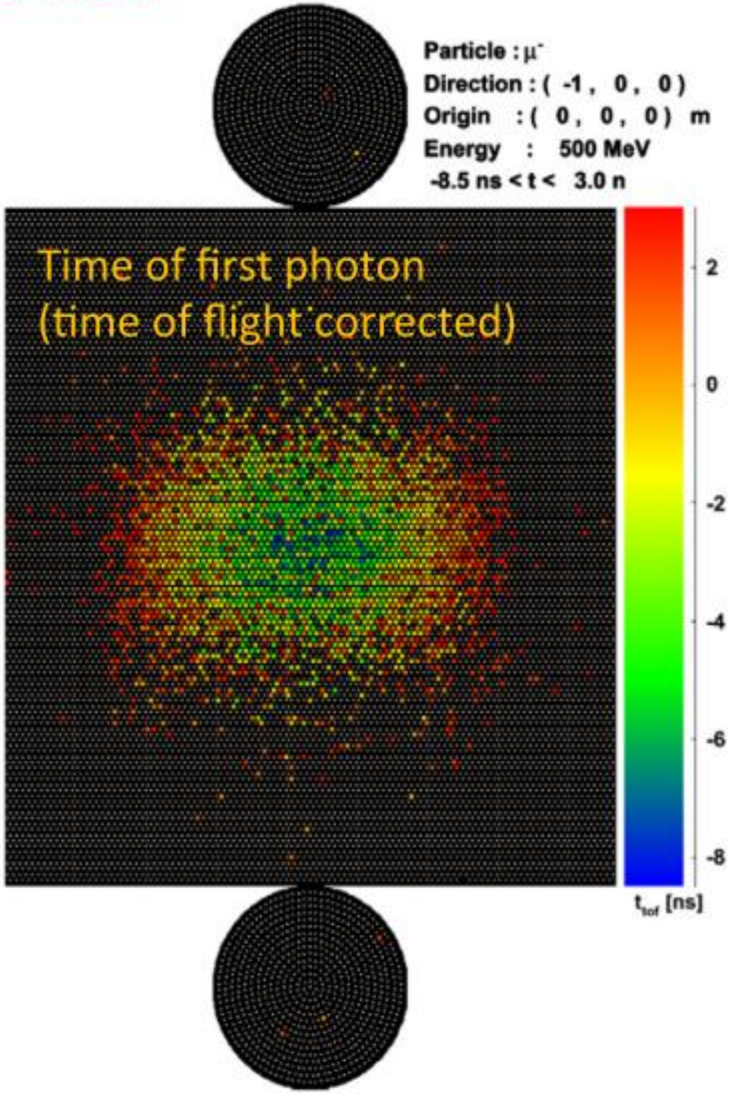
***Preliminary** results: Monte-Carlo simulation based on recent results of PSD parameter on LAB scintillators*

Tracking in the sub-GeV range

Use patterns of first photon arrival times + integrated charge per PMT

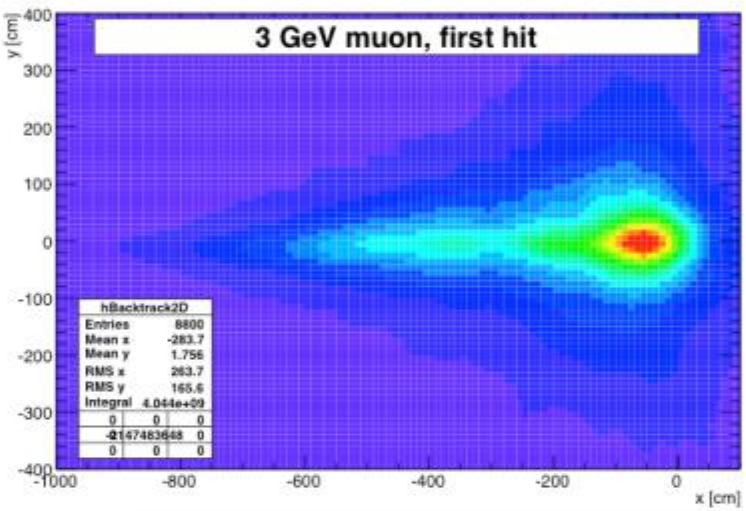
Example: 500 MeV muon

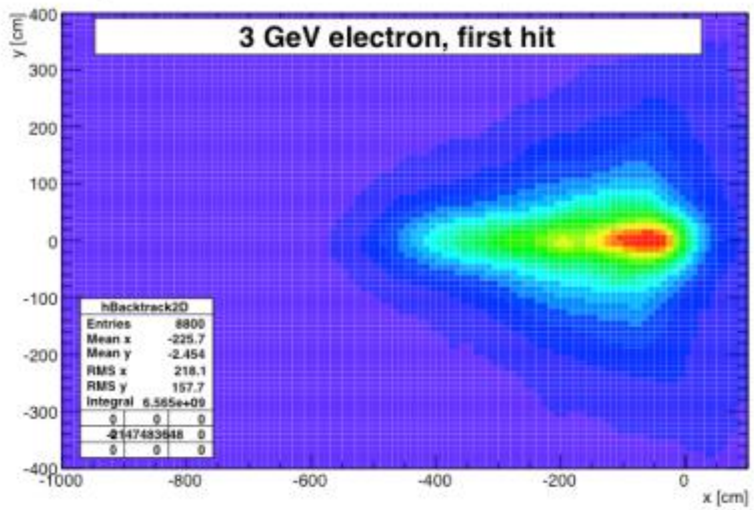


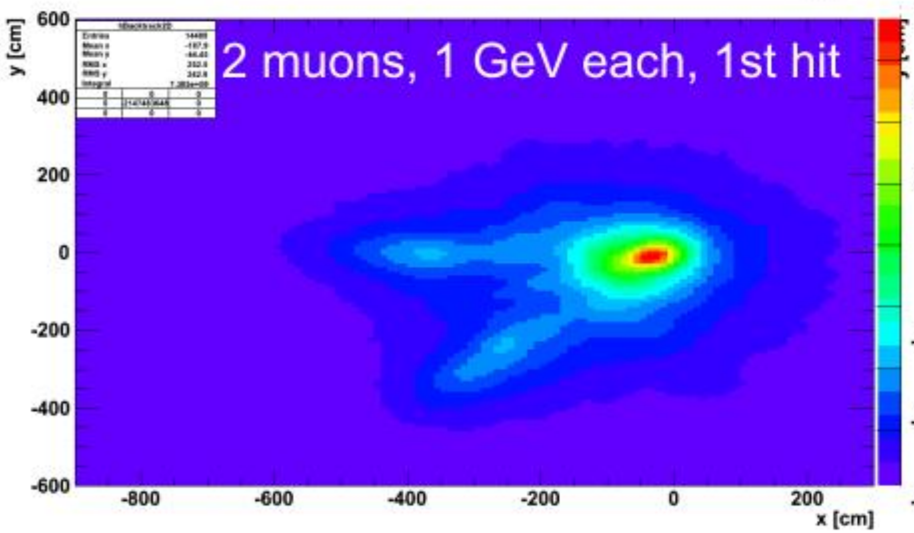


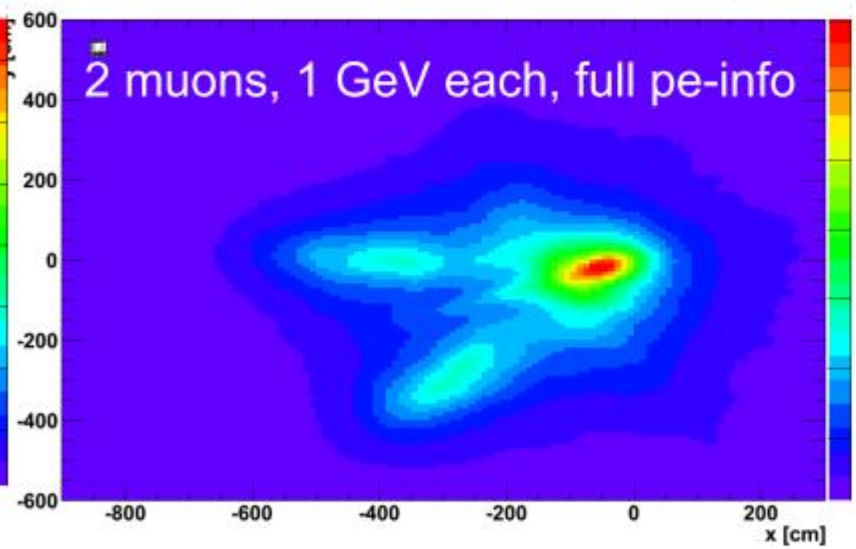
Tracking in the 1-5 GeV range

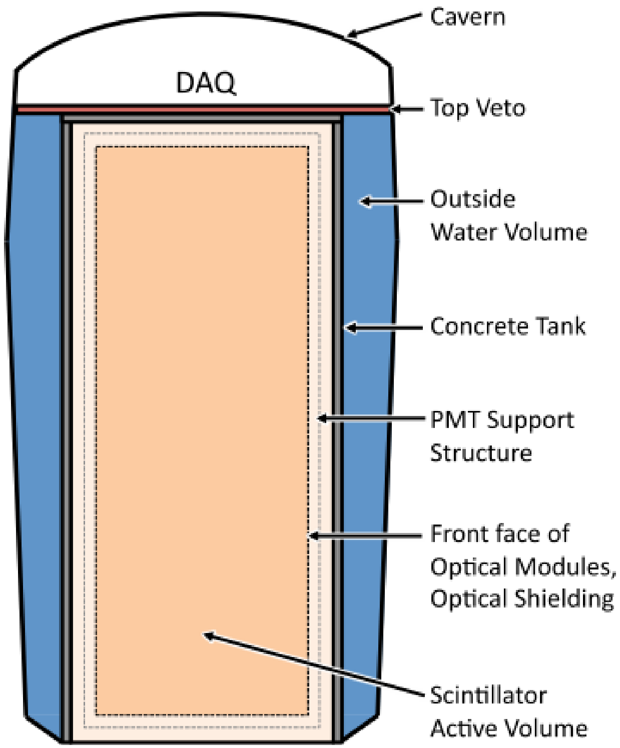
Backtracking method: use individual pulse shapes from each PMT

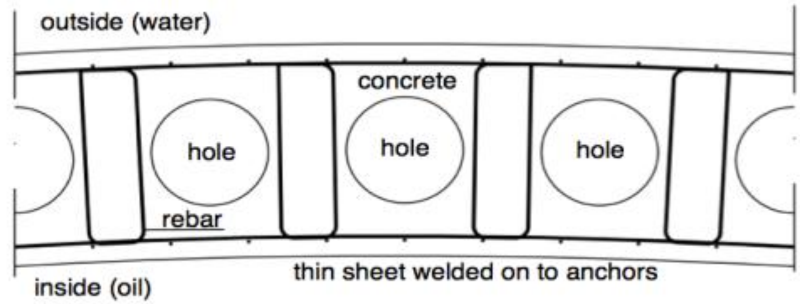


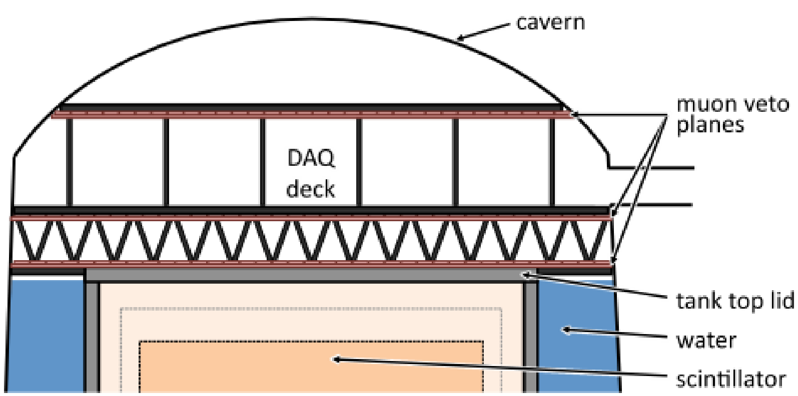


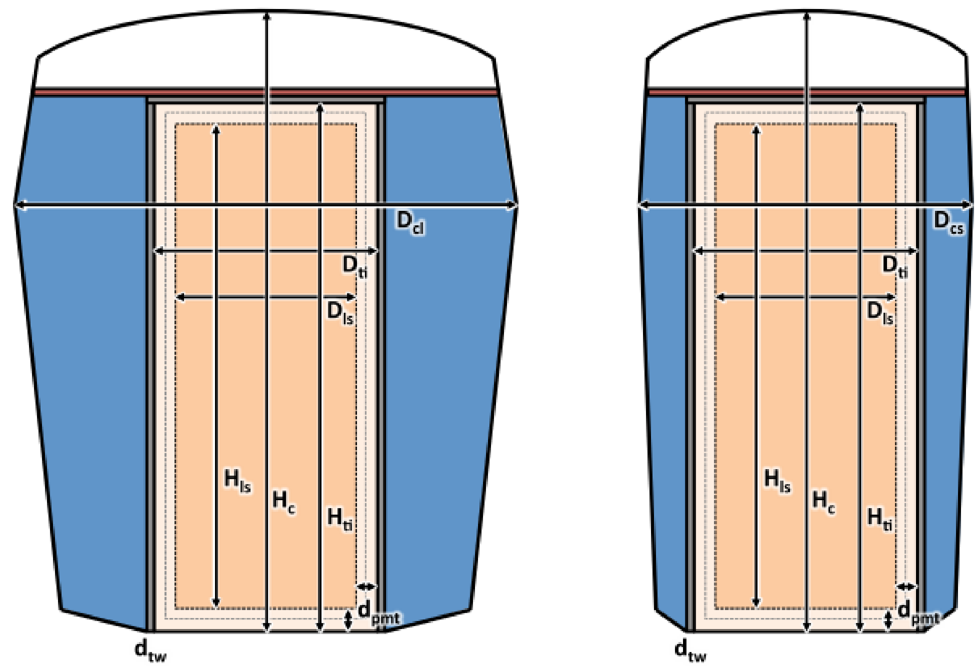


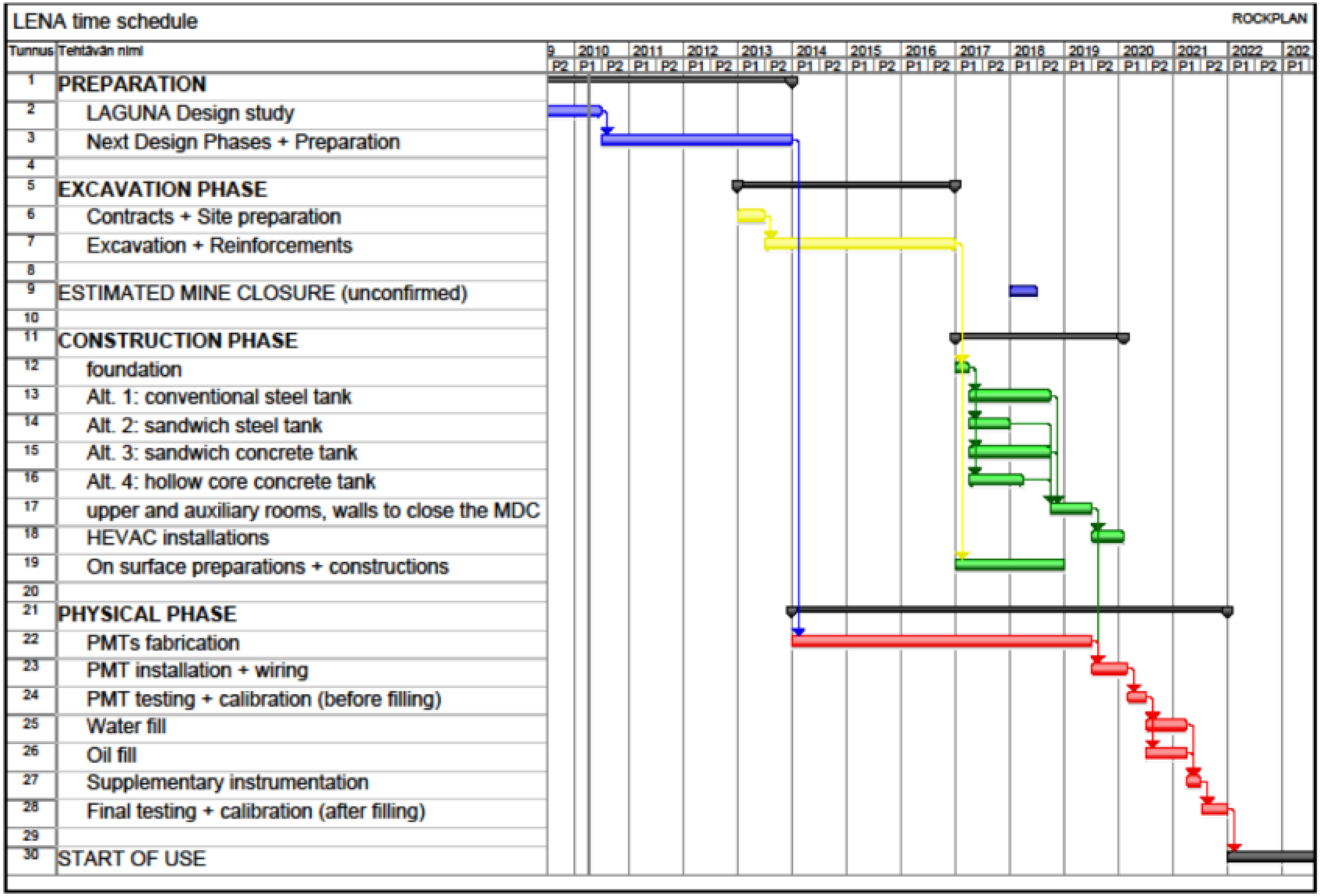



Cavern
DAQ
Top Veto
Outside
Water Volume
Concrete Tank
PMT Support
Structure
Front face of
Optical Modules,
Optical Shielding
Scintillator
Active Volume


outside (water)
concrete
hole
hole
hole
rebar
thin sheet welded on to anchors
inside (oil)


cavern
muon veto
planes
DAQ
deck
tank top lid
water
scintillator


D_{cl}
D_{ti}
D_{ls}
H_{ls}
H_c
H_{ti}
d_{pmt}
d_{tw}
D_{cs}
D_{ti}
D_{ls}
H_{ls}
H_c
H_{ti}
d_{pmt}
d_{tw}


LENA time schedule
ROCKPLAN
Tunnus
Tehtävän nimi
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
P1
P2
1 PREPARATION
2 LAGUNA Design study
3 Next Design Phases + Preparation
4
5 EXCAVATION PHASE
6 Contracts + Site preparation
7 Excavation + Reinforcements
8
9 ESTIMATED MINE CLOSURE (unconfirmed)
10
11 CONSTRUCTION PHASE
12 foundation
13 Alt. 1: conventional steel tank
14 Alt. 2: sandwich steel tank
15 Alt. 3: sandwich concrete tank
16 Alt. 4: hollow core concrete tank
17 upper and auxiliary rooms, walls to close the MDC
18 HEVAC installations
19 On surface preparations + constructions
20
21 PHYSICAL PHASE
22 PMTs fabrication
23 PMT installation + wiring
24 PMT testing + calibration (before filling)
25 Water fill
26 Oil fill
27 Supplementary instrumentation
28 Final testing + calibration (after filling)
29
30 START OF USE

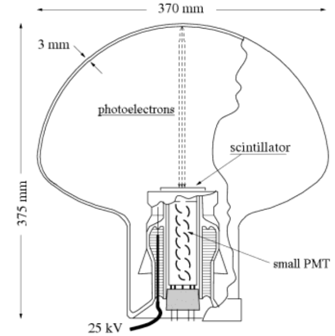
Which sensors could fulfill the requirements?

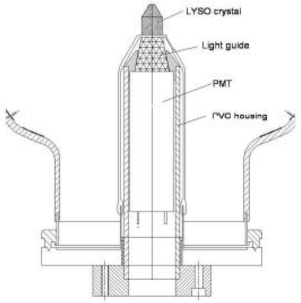
- Hybrid detectors

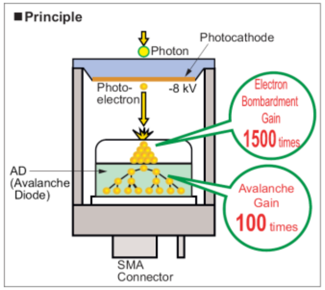
Crucial question:
Available in high quantities in time for construction?

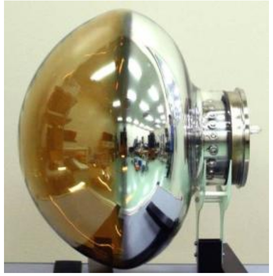
Possibly yes:

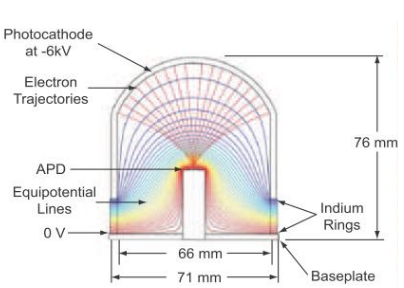
- Layout: Photocathode, HV, scintillator crystal, PMT
  - QUASAR
    - \+ better time resolution, lower dark count + afterpulsing
    - − no manufacturer, dynamic range possibly too small
  - X-HPD
    - − possibly too high dark count + too small dyn. range
- Layout: Photocathode, HV, APD
  - HAPD
    - \+ should be commercially available soon
    - − dyn. range possibly too small
  - QUPID
    - − small size, designed for LAr/LXe, dark count possibly too high, dyn. range poss. too low, detection efficiency not yet known











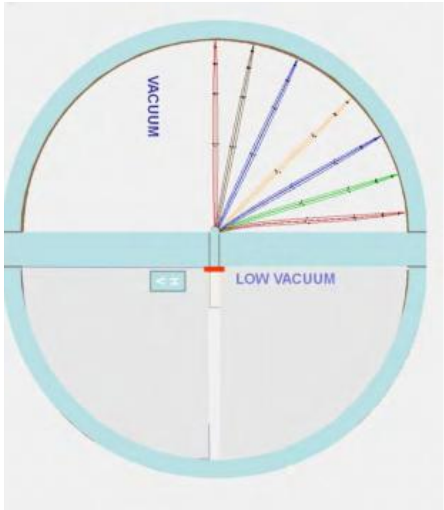
Which sensors could fulfill the requirements?

- Hybrid detectors

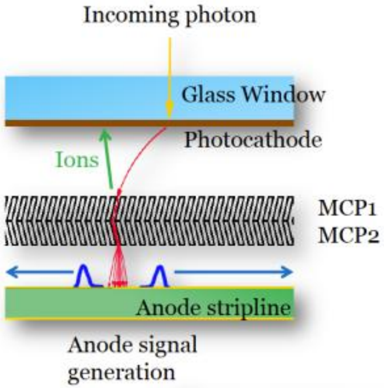
Crucial question:
Available in high quantities in time for construction?

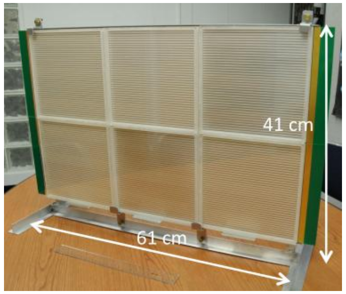
Probably not:

- Layout: Photocathode, HV, scintillator crystal, SiPM
  - Abalone
    - \+ simple, robust + cheap design
    - − Prototypes not yet stable under atmospheric pressure



- Layout: Photocathode, 2 microchannel plates → anode striplines read out at both ends
  - LAPPD
    - \+ ps time resolution, large area, position sensitive, cheap(?)
    - − no complete prototype yet





How can we determine the missing properties?

Measurements at the Borexino PMT testing facility

	R6091 (3") with 1.8" aperture	R6594 (5")	R5912 (8")	R7081 (10")	ETL9351 (8") no. 1732	ETL9351 (8") average
Voltage	+1760V	+1670V	+1425V	+1520V	+1500V	≈+1450V
Gain	$1.0\cdot10^7$	$1.0\cdot10^7$	$1.3\cdot10^7$	$1.3\cdot10^7$	$1.0\cdot10^7$	$1.0\cdot10^7$
pe/trigger (npe)	2.21%	5.53%	1.83%	2.91%	4.78%	5.19%
TTS (FWHM) (manufacturer)	1.89ns (2.0ns)	1.91ns (1.5ns)	2.04ns (2.4ns)	3.05ns (3.5ns)	2.16ns	2.76ns
EP (all non-gaussian)	0.14%	2.95%	1.93%	0.57%	1.23%	0.75%(3σ)
LP (all non-gaussian)	27.29%	34.16%	55.01%	42.90%	8.70%	-
LP (after NP peak)	6.26%	3.13%	2.88%	3.09%	4.08%	7.90%(3σ)
DN	0.192kHz	(5.23kHz)	1.62kHz	2.64kHz	1.72kHz	2.48kHz
DN/cm²	12.1 Hz/cm²(eff.)	(46.3 Hz/cm²)	5.1 Hz/cm²	5.3 Hz/cm²	5.3 Hz/cm²	7.7 Hz/cm²
Ion AP	0.14%	0.94%	6.62%	5.12%	2.57%	4.9%
p/V	2.04	3.88	2.99	3.09	2.25	2.10

TECHNICAL INFORMATION

MAY 2012

PHOTOMULTIPLIER TUBE R11780

302 mm (12 inch) Diameter, 10-stage, Hemispherical Window Bialkali Photocathode, Head-on Type

SPECIFICATIONS

GENERAL

Parameter		Description / Value	Unit
Spectral Response		300 to 650	nm
Wavelength of Maximum Response		420	nm
Photocathode Material		Bialkali	—
Window Material		Borosilicate glass	—
Minimum Effective Area		φ280	mm
Dynode	Structure	Box & Line	—
	Number of Stages	10	—
Capacitances	Anode to Last Dynode	Approx. 13	pF
	Anode to All Other Dynodes	Approx. 18	pF
Base		20-Pin Base / JEDEC No. B20-102	—
Suitable Socket		E678-20B (supplied)	—
Weight		Approx. 2200	g
Operating Ambient Temperature		-30 to +50	°C
Storage Temperature		-30 to +50	°C

MAXIMUM RATINGS (Absolute Maximum Values)

Parameter		Value	Unit
Supply Voltage	Between Anode and Cathode	2700	V
	Between Anode and Last Dynode	300	V
Average Anode Current		0.1	mA
Average Cathode Current		100	nA
Ambient Pressure (Gauge)		0.8	MPa

CHARACTERISTICS (at 25 °C)

Parameter		Min.	Typ.	Max.	Unit
Cathode Sensitivity	Luminous (2856 K)	—	70	—	μA/lm
	Radiant at 420 nm	—	72	—	mA/W
	Blue Sensitivity Index (CS 5-58)	—	9	—	—
	Quantum Efficiency at 380 nm to 420 nm	—	22	—	%
Anode Sensitivity	Luminous (2856 K)	—	700	—	A/lm
	Radiant at 420 nm	—	7.2×10^5	—	A/W
Gain		—	1×10^7	—	—
Supply Voltage for Gain of 1×10^7		—	2000	2500	V
Anode Dark Current (after 30 min storage in darkness)		—	200	1000	nA
Dark Count (after 24 h storage in darkness) *1		—	10 000	20 000	s^{-1}
Time Response	Anode Pulse Rise Time	—	4	10	ns
	Electron Transit Time	—	70	—	ns
	Transit Time Spread (FWHM) *1 *2	—	2.6	—	ns
Pre Pulse *1 *2	10 ns to 80 ns before Main Pulse	—	0.5	2	%
Delay Pulse *1 *2	15 ns to 100 ns after Main Pulse	—	4	5	%
After Pulse *1 *2	100 ns to 16 μs after Main Pulse	—	10	20	%
P/V (Peak to Valley) Ratio *1 *2		2.0	2.8	—	—

*1: LLD: 1/4 p.e. *2: at single p.e.

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K		Dy1		F		Dy2		Dy3		Dy4		Dy5		Dy6		Dy7		Dy8		Dy9		Dy10		P
Ratio		11.3		0.6		3.4		5		3		2		1		1		1		1		1		1	
Capacitors in μF																				0.01		0.01		0.01	

Supply Voltage: 2000 V, K: Cathode, Dy: Dynode, P: Anode, F: Focus

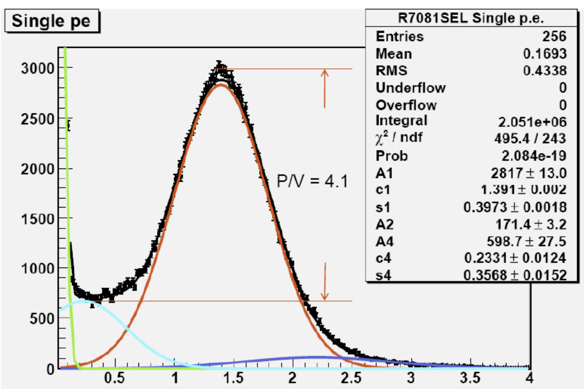
Projects

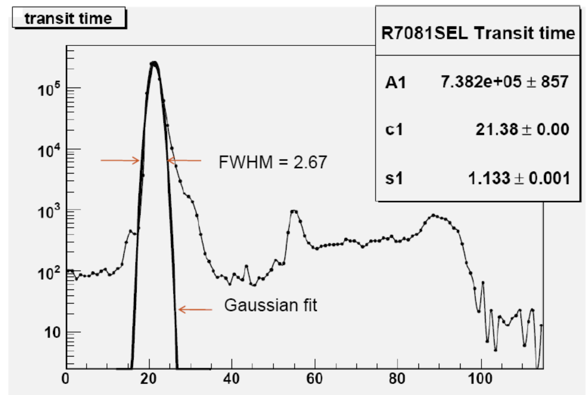
Paolo Lombardi

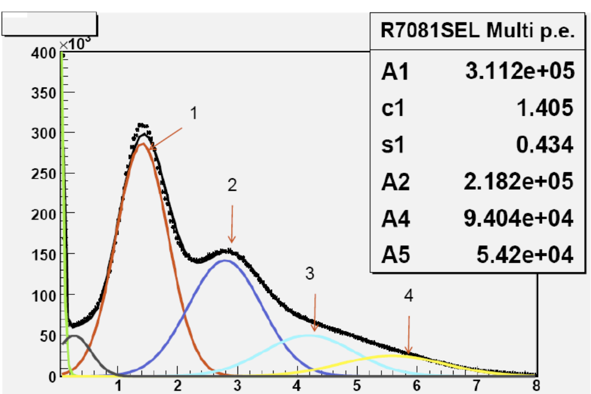
Paolo Lombardi,
LENA Meeting 2010-07-05

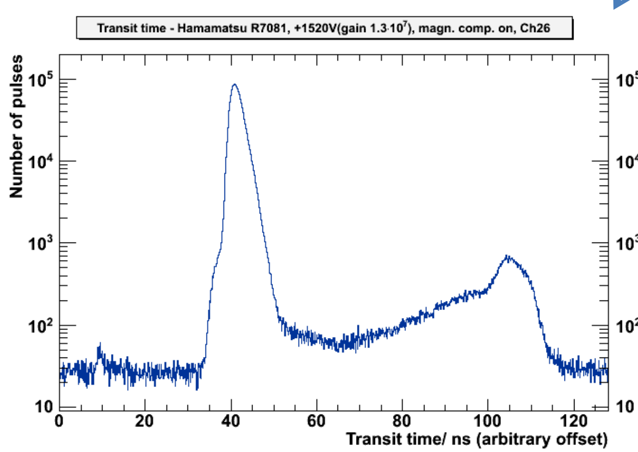
- Study of HQE PMTs:
  - Measured Hamamatsu *super-bialkali PMTs* (≈34% peak-QE): R6594-SEL, R5912-SEL, R7081-SEL

    → Direct comparison with *standard photocathode PMTs* measured @ Borexino PMT testing facility or Garching setup possible









- Next measurements:
  - Cathode uniformity scan
  - Magnetic field effect
  - Gain vs voltage response
  - Dark noise vs temperature
  - Long term stability

Pressure encapsulations

- New PMTs being developed for LBNE:
  - Designed for 11bar (81m tank height) + good performance, will have housing around pins (most sensitive area)
  - Hamamatsu R11780: 12“
    - Designed from scratch
    - Two independent simulations by Hamamatsu + LBNE → fulfills pressure requirements
    - ≈100 prototypes build → sensor properties look mostly very good by now, will commence pressure tests soon
    - Did pressure tests for R7081 (10“): designed for 7bar, all survived until 10bar, some above 15bar
  - ETEL D784: 11“
    - Designed from scratch
    - Simulations → fulfills pressure requirements
  - Both manufacturers claim that designs for higher pressure should be possible, problem is not pressure but pressure + high purity water for several 10y

- ***LENA: Do we need pressure encapsulations: for the ID? for the OD?***
  - ID (100m height): LAB → ≈9.8bar
  - OD (100m height): water → ≈11bar + ultrapure water for 30y
    a) Use encapsulations
    b) Develop new PMT type which can withstand 13+bar
    c) Decrease height

Pressure withstanding PMT encapsulations for LENA:
Pressure simulations

- Simulate behaviour under pressure with a Finite Elements Analysis (FEA) simulation software
  - Engineering drawings and FEA pressure simulations were done with same software

- Software: SolidWorks Educational Edition Academic Year 2010-2011 SP4.0, *Simulation Premium package*
- Settings: Linear static study, 12bar pressure, node distance 3mm ± 0.15mm
- Materials: High impact resistant acrylic glass, 1,4404 stainless steel X2CrNiMo17-12-2
- Computer: Intel i7-2600, 8GB DDR3-RAM, AMD Radeon HD 6450 1GB GDDR3, Win7 Prof. 64bit

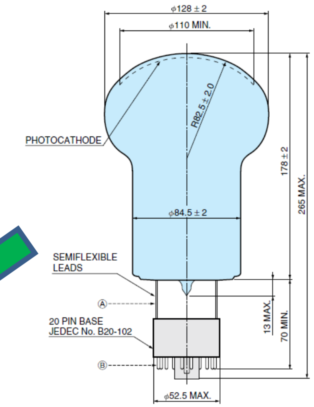
- So far designs + simulations for 5 candidate PMTs:
  - Hamamatsu: R7081 (10“), R5912 (8“), R6594 (5“)
  - Electron Tubes Enterprises Ltd.: 9354 (8“), 9823 (5“)

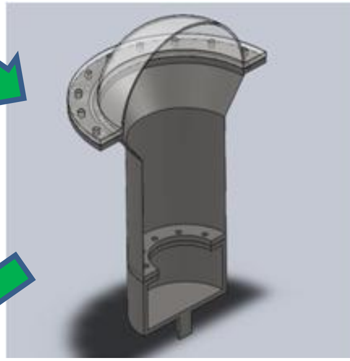
German Beischler

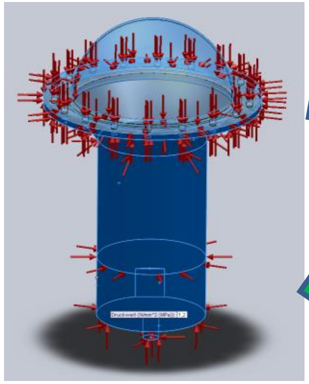
- *Was treated in a bachelor thesis by **German Beischler***
  - *In consultance with Harald Hess (head of workshop + SolidWorks expert of our chair)*
  - *Continues these studies!*

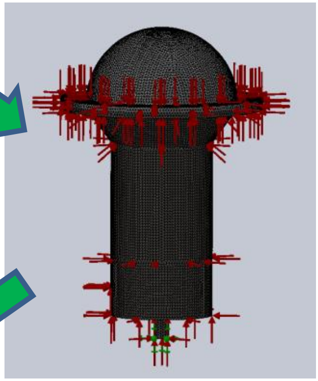
Pressure withstanding PMT encapsulations for LENA:

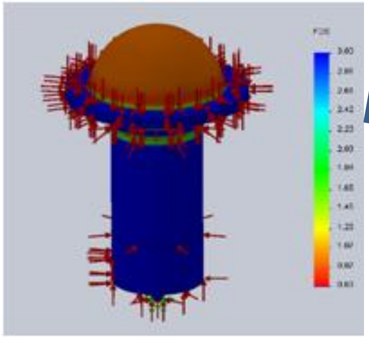
Pressure simulations









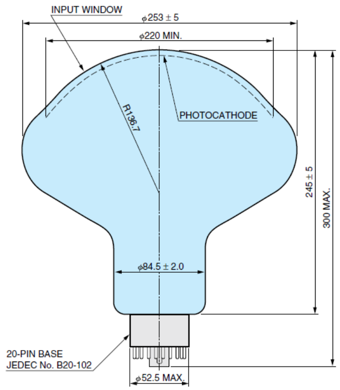


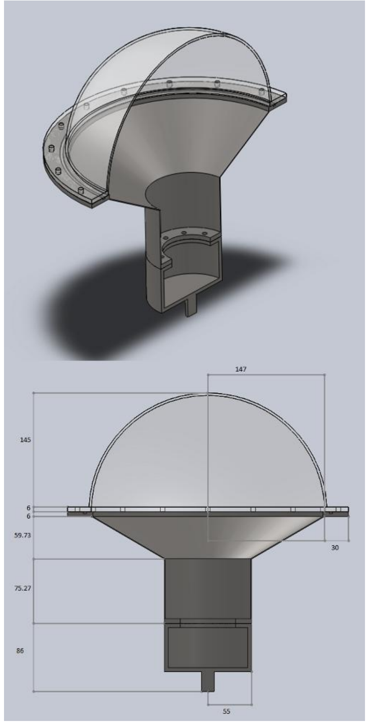
Procedure:

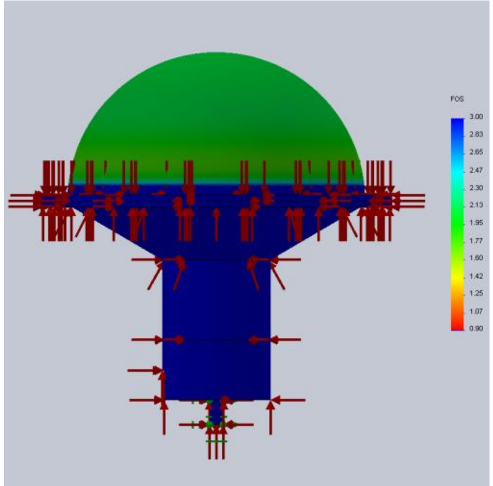
- Import PMT contour from engineering drawing in datasheet
- Rotate to obtain model of PMT
- Construct encapsulation based on PMT dimensions and experience from design of the Borexino + Double Chooz encapsulation
- Simulate encapsulation with 12bar pressure applied
  - Apply forces → meshing → simulate to determine factor of safety
  - Vary thicknesses of acrylic glass + stainless steel to find minimum values
- Compare results for different designs regarding weight (U, Th, K impurities in materials), surface (adsorbed Rn) and construction costs

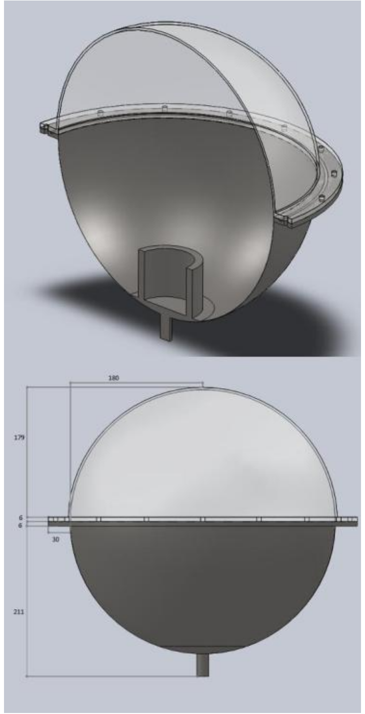
Pressure withstanding PMT encapsulations for LENA

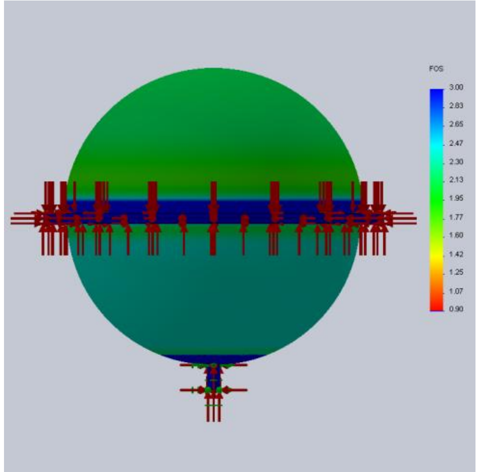
Pressure simulation results: Hamamatsu R7081 (10“)











<u>Conical encapsulation:</u>

Steel: 2mm thickness, 4.38kg

Acrylic glass: 4mm thickness, 0.86kg

Total surface: 0.69m²

<u>Spherical encapsulation:</u>

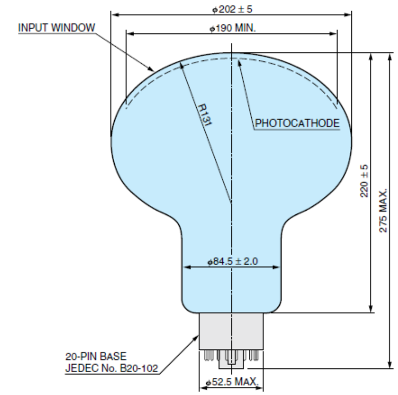
Steel: 0.5mm thickness, 4.08kg

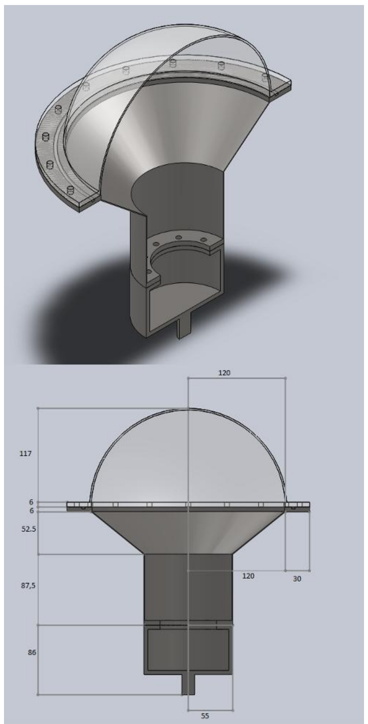
Acrylic glass: 5mm thickness, 1.48kg

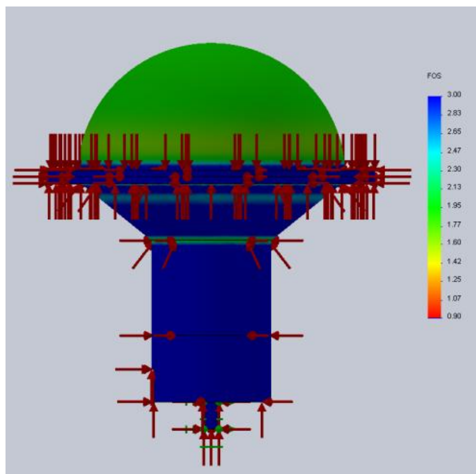
Total surface: 1.01m²

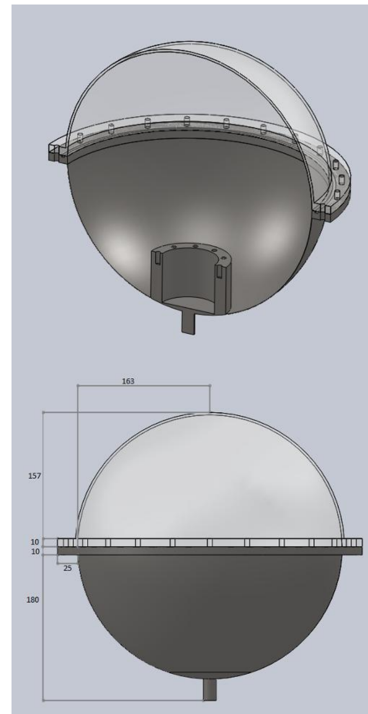
Pressure withstanding PMT encapsulations for LENA

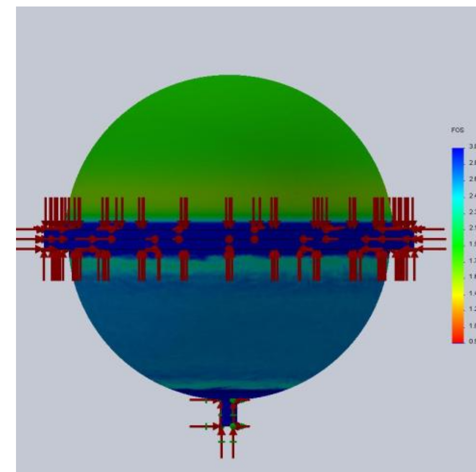
Pressure simulation results: Hamamatsu R5912 (8")











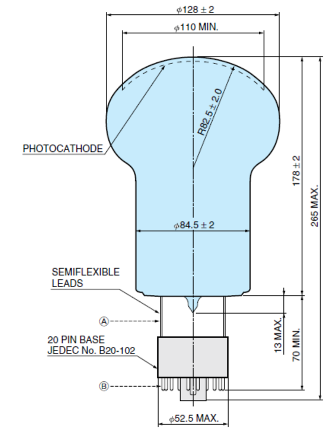
<u>Conical encapsulation:</u>

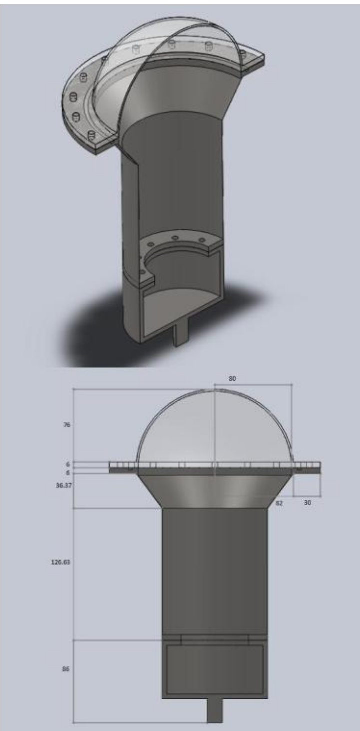
Steel:	1mm thickness,	3.24kg
Acrylic glass:	3mm thickness,	0.50kg
Total surface:	0.53m^2	

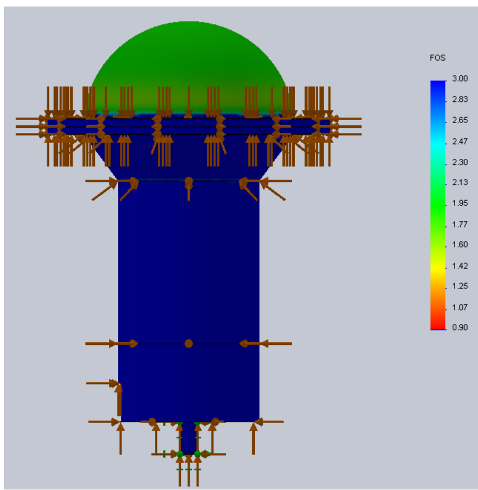
<u>Spherical encapsulation:</u>

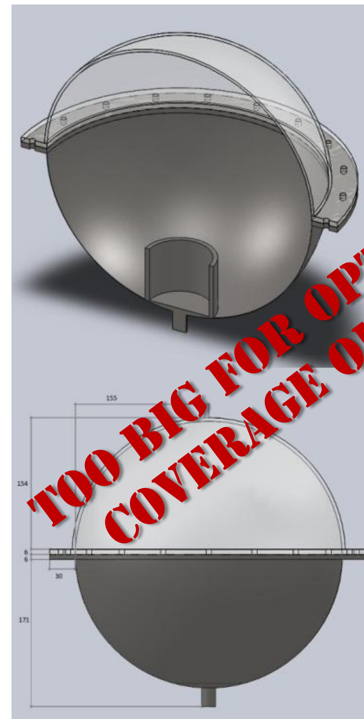
Steel:	0.5mm thickness,	4.66kg
Acrylic glass:	4mm thickness,	1.10kg
Total surface:	0.83m^2	

Pressure simulation results: Hamamatsu R6594 (5“)

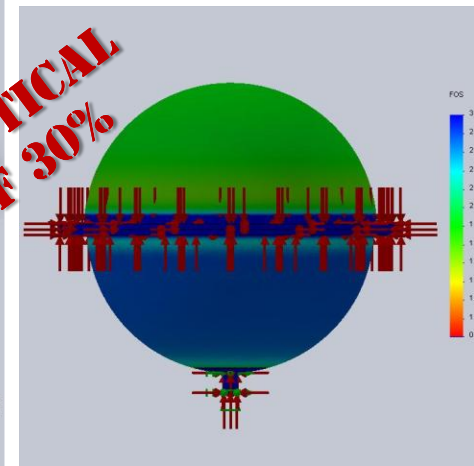








TOO BIG FOR OPTICAL COVERAGE OF 30%



<u>Conical encapsulation:</u>

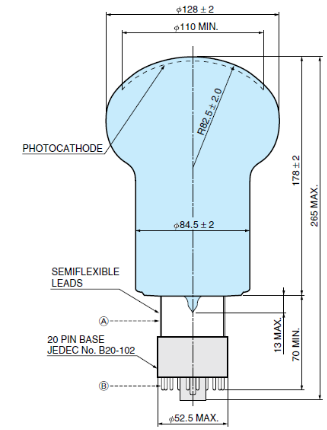
Steel:	1mm thickness,	2.77kg
Acrylic glass:	2mm thickness,	0.22kg
Total surface:	$0.37m^2$	

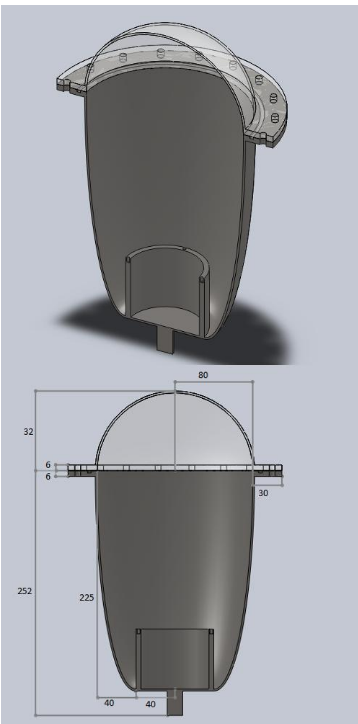
<u>Spherical encapsulation:</u>

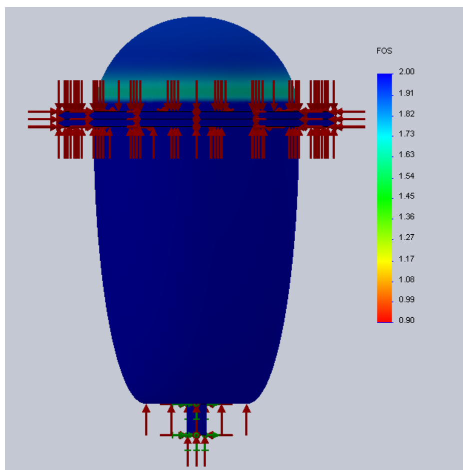
Steel:	0.5mm thickness,	2.75kg
Acrylic glass:	4mm thickness,	0.94kg
Total surface:	$0.78m^2$	

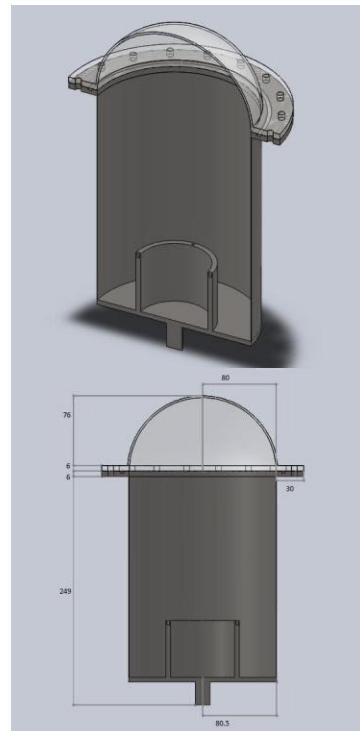
Pressure withstanding PMT encapsulations for LENA

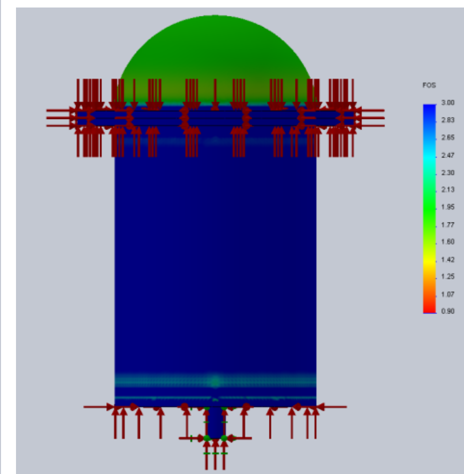
Pressure simulation results: Hamamatsu R6594 (5“)











<u>Elliptical encapsulation:</u>

Steel: 2mm thickness, 3.06kg

Acrylic glass: 2mm thickness, 0.22kg

Total surface: 0.41m²

<u>Cylindrical encapsulation:</u>

Steel: 0.5mm thickness, 2.61kg

Acrylic glass: 2mm thickness, 0.22kg

Total surface: 0.46m²

Pressure withstanding PMT encapsulations for LENA

Next steps:

DESIGN + SIMULATIONS

- Further crosschecks
- More exact simulations: reduce node distance (locally or globally), use adaptive methods
- Complete design (fixture for PMT inside encapsulation, filling valve) + create complete optical module: incorporate Mu-metal, Winston Cones, connections to other PMTs + wall
- Optimize encapsulations for least weight + least production costs
- Create + simulate designs for further PMTs (R6091, 9822, R11780, D784)
- Distortion analysis
- Aging simulation

BUILD + TEST PROTOTYPES

- Build prototype for PMT of choice
- Test in pressure tank
    - Adapt design to meet requirements
    - Influence of PMT implosion on adjacent encapsulations